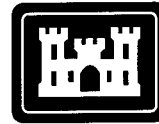


ERDC/SL TR-00-1

Structures Laboratory



**US Army Corps  
of Engineers®**  
Engineer Research and  
Development Center

## 1996 Singapore Ground Shock Test

Donald W. Murrell and Charles E. Joachim

April 2000

20000530 035

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.



PRINTED ON RECYCLED PAPER

# 1996 Singapore Ground Shock Test

by Donald W. Murrell, Charles E. Joachim

Waterways Experiment Station  
U.S. Army Engineer Research and Development Center  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199

Final report

Approved for public release; distribution is unlimited

Prepared for   Lands and Estates Organization  
                  Ministry of Defence  
                  1 Depot Road, #12-05  
                  Singapore 109679  
                  Republic of Singapore

### **Engineer Research and Development Center Cataloging-in-Publication Data**

Murrell, Donald W.

1996 Singapore ground shock test / by Donald W. Murrell, Charles E. Joachim ; prepared for Lands and Estates Organization, Ministry of Defense.

90 p. : ill. ; 28 cm. — (ERDC/SL ; TR-00-1)

Includes bibliographic references.

1. Soils — Vibration — Singapore. 2. Shock (Mechanics) — Measurement — Singapore. 3. Underground storage — Singapore. 4. Shock waves — Testing — Singapore. I. Joachim, Charles E. II. United States. Army. Corps of Engineers. III. Engineer Research and Development Center (U.S.) IV. Structures Laboratory (U.S.) V. Singapore. Ministry of Defence. VI. Title. VII. Series: ERDC/SL TR ; 00-1. TA7 E8 no.ERDC/SL TR-00-1

# Contents

---

Preface .....	vii
1—Introduction .....	1
Background.....	1
Requirements.....	1
Proposed R&D Program .....	2
Development of the 1996 Singapore Ground Shock Test.....	2
Objectives .....	3
Test Site Location and Geology .....	3
2—Procedure.....	7
Test Description.....	7
Chamber and Tunnel Dimensions.....	7
Explosive Charge .....	10
Instrumentation: Plan and Procedures.....	10
General .....	10
Ground shock measurements .....	12
Surface motion measurements .....	12
Airblast measurements.....	12
Instrumentation: Transducers.....	12
Ground shock gages.....	12
Surface motion gages.....	16
Airblast gages .....	16
Instrumentation: Protection Systems.....	16
Accelerometer canisters .....	16
Airblast gage housings.....	17
Cable and cable protection.....	17
Grouting.....	17
Instrumentation: Data Recording .....	19
Recording system.....	19
Predictions for gage ranging .....	19
3—Results and Discussion.....	21
General.....	21
Free-Field Ground Shock Measurements.....	21
Instrument performance .....	21

Shock arrival times .....	23
Accelerometers .....	23
Particle velocity .....	28
Surface Motions .....	28
Near-surface seismic velocity survey .....	28
Accelerations and velocities .....	28
Airblast Results .....	38
Instrument performance .....	38
Arrival times .....	38
Peak pressures .....	38
Peak impulse .....	44
4—Conclusions and Recommendations .....	46
Conclusions .....	46
Recommendations .....	46
References .....	47
Appendix A: 1996 Singapore Ground Shock Time-Histories .....	A1
Appendix B: Singapore Ground Shock Test: Airblast Pressure Time-Histories .....	B1
SF 298 .....	

## List of Figures

---

Figure 1. Layout of test drifts in Lynchburg Mine for 1/3-scale underground magazine blast effects tests .....	5
Figure 2. Approximate geologic profile for vertical gage hole above Chamber 2 .....	6
Figure 3. Front view of sandbag and rock rubble barrier inside the entrance to Chamber 2 .....	8
Figure 4. Configuration and dimensions of test chamber (Chamber 2) .....	9
Figure 5. Explosive charge design for Singapore Ground Shock Test .....	11

Figure 6.	Ground shock measurement locations in vertical gage hole for Singapore Ground Shock Test .....	13
Figure 7.	Seismic sensor and shot point overlay on overburden surface above the Linchburg Mine, Singapore Ground Shock Test.....	14
Figure 8.	Airblast gage layout for Singapore Ground Shock Test.....	15
Figure 9.	Airblast gage debris shield.....	18
Figure 10.	Crater in the floor of Chamber 2 produced by the explosive charge detonated for the Singapore Ground Shock Test .....	22
Figure 11.	Ground shock arrival times versus range .....	25
Figure 12.	Scaled peak acceleration versus scaled range .....	26
Figure 13.	Location of U.S. Phase 3 Intermediate-Scale tests .....	27
Figure 14.	Peak particle velocity versus scaled range .....	31
Figure 15.	Seismic profile from refraction survey of overburden above test chamber at Linchburg Mine.....	32
Figure 16.	Vertical particle velocity-time histories from seismic transducers located on the overburden surface above Chamber 2, Singapore Ground Shock Test .....	33
Figure 17.	Horizontal (E-W) particle velocity-time histories from seismic transducers located on the overburden surface above Chamber 2, Singapore Ground Shock Test .....	34
Figure 18.	Horizontal (N-S) particle velocity-time histories from seismic transducers located on the overburden surface above Chamber 2, Singapore Ground Shock Test .....	35
Figure 19.	Peak particle velocity (peak to peak) versus horizontal distance from the top of the instrument hole, Singapore Ground Shock Test.	36
Figure 20.	Peak particle velocity (peak to peak) versus slant distance from the center of the explosive charge, Chamber 2, Singapore Ground Shock Test .....	37
Figure 21.	Comparison of vertical surface motion particle velocities (open circle symbols) with the radial free-field velocities, all as a function of scaled range from the charge center, Singapore Ground Shock Test .....	40

Figure 22. Airblast shock front arrival time versus distance from rear wall of Chamber 2, Singapore Ground Shock Test.....	41
Figure 23. Typical underground airblast pressure-time history with shock and gas components, Singapore Ground Shock Test.....	42
Figure 24. Peak overpressure versus distance from rear wall of Chamber 2, Singapore Ground Shock Test .....	43
Figure 25. Peak overpressure impulse versus distance form real wall of Chamber 2, Singapore Ground Shock test .....	45

## List of Tables

---

Table 1. Results of Grout Sample Properties Tests .....	20
Table 2. Free-Field Ground Shock Data Summary .....	24
Table 3. Locations of Seismic Surface Motion Gages, Refraction Survey Shot Points, and External Airblast Gages.....	29
Table 4. Seismic Surface Motion Data Summary.....	30
Table 5. Airblast Data Summary .....	39



# Preface

---

The Republic of Singapore sponsored this research effort under provisions of the U.S. Army Foreign Military Sales Case No. SN-B-HAA. The study was conducted by the Geomechanics and Explosion Effects Division (GEED), Structures Laboratory (SL), Waterways Experiment Station (WES), U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. The experiments were performed in an underground test area of the Lynchburg Mine near Magdalena, NM, in June 1996.

The Program Monitor was Mr. Lim Chee Hiong, Deputy Director, Lands and Estates Organization, Ministry of Defense, Republic of Singapore.

The U.S. Program Manager for this study was Mr. Landon K. Davis, GEED. Mr. Donald W. Murrell was the Project Engineer, and Mr. Charles E. Joachim was the Test Manager. Messrs. Murrell and Joachim are the authors of this report. WES staff members assisting in the study were Messrs. T. G. Ray, and B. P. Dent, Jr., GEED, and Messrs. F. D. Shirley, and G. S. Cronia, Jr., Instrumentation Systems Development Division, Information Technology Laboratory, WES, ERDC. Ms. Marion P. Alberts, GEED, assisted with data processing, and Meses. Donna B. Rowland and Corrie Spivey, GEED, assisted in preparation of the report. Mr. R. C. Correa, Energetic Materials Research and Testing Center, New Mexico Institute of Mining and Technology, supervised explosive handling and mine reentry safety inspection.

A seismic refraction survey was performed on the surface above the test chambers at the Lynchburg Mine by personnel from Test Division, Counter Proliferation Directorate, Defense Threat Reduction Agency (DTRA). Mr. J. A. Leverette, DTRA, also measured surface seismic signals during the test. The seismic investigations were funded in part by DTRA and were performed under the direct supervision of Dr. R. E. Reinke, DTRA.

The work reported herein was performed under the supervision of Mr. Andrew E. Jackson, Acting Chief, GEED, and Dr. Michael J. O'Connor, Acting Director, SL.

At the time of publication of this report, Dr. Lewis E. Link was acting Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

# 1 Introduction

---

## Background

### Requirements

The Singapore Ground Shock Test was conducted at the Linchburg Mine near Magdalena, NM, where WES performed previous experiments related to Underground Ammunition Storage Technologies (UAST) research. The UAST program was designed to (a) develop more accurate predictions of the hazard distances (Quantity-Distance, or QD) for inhabited buildings associated with underground magazines, and (b) investigate specific design features that could significantly reduce the QDs. The goal was to technically demonstrate that the QDs for underground magazines could be reduced to 10 percent or less of those required for above-ground magazines.

The term “underground magazine” refers to an ammunition storage facility that is excavated as a system of access tunnels and storage chambers in rock. The explosion hazards of concern normally include the airblast, ejected debris, and ground shock produced by an accidental explosion of the stored ammunition.

In 1995, the Ministry of Defense of the Republic of Singapore (SN/MOD) announced that the use of underground magazines was being considered as a means of storing defense ammunition reserves in Singapore. Since there are essentially no large hills or mountains in Singapore, an alternative concept was being considered, i.e., to place the storage chambers in rock deep below the surface, with access tunnels that ramp down from the surface.

With this concept, the length and configuration of the access tunnels would be such that the airblast and debris hazards would be greatly reduced (assuming the storage chambers are deep enough to preclude breaching to the surface). However, with the severe limitations on available real estate in Singapore, it is probable that the allowable hazard area on the surface will be very small—perhaps even non-existent. With the airblast and debris hazards essentially eliminated, the threat of primary concern becomes the ground shock and resulting surface motions generated by an accidental explosion.

## **Proposed R&D program**

The U.S. Army Engineer Waterways Experiment Station (WES) was the lead U.S. technical agency for the UAST program. At the recommendation of the U.S. Department of Defense Explosives Safety Board (DDESB), SN/MOD representatives proposed to WES the possibility of a cooperative US/SN research program to investigate further the ground shock hazards associated with deep underground magazines.

WES responded in late 1995 with a rough, preliminary proposal to SN/MOD for a joint U.S./Singapore R&D program (Davis 1995). The proposed program was structured around three principal tasks:

Task 1: Development of Improved Predictions of Ground Shock from Explosions in Underground Chambers

Task 2: Investigation of Methods for Mitigating Ground Shock from Explosions in Underground Chambers

Task 3: Revision of Ground Shock Hazard Criteria for Inhabited Buildings

Task 1 was funded (with some modifications) by SN/MOD and provided the basis for the study described in this report.

## **Development of the 1996 Singapore ground shock test**

During the time the preliminary proposal was being reviewed and developed, WES was scheduled to complete a final series of large-scale explosive tests for the UAST program. The tests were conducted at WES's underground test facility in the Linchburg Mine near Magdalena, NM. While a number of measurements were made of ground shock produced by the UAST experiments, the primary emphasis was on the airblast, debris, and thermal effects generated within the tunnel/chamber system. Those UAST tests that did involve ground shock measurements were also highly idealized, in that the explosive charges were constructed of near solid explosive, and were aligned along the central, horizontal axis of the chambers. The close-in ground shock was measured in several directions to determine if asymmetries in shock attenuation rates would occur due to the horizontal structure of the local rock geology.

The final UAST test was designated as the UAST Validation Test and was designed to validate the blast effects control and prediction methodologies developed under the program. The Validation Test involved the detonation of 1955 kg of explosives in a chamber volume of 70 m<sup>3</sup>, located approximately 115 m below the surface in a limestone rock geology.

The UAST Validation Test offered an excellent opportunity to obtain information that would directly support the underground magazine problem for Singapore, i.e., the magnitude and characteristics of ground shock and the resulting surface motions above a detonation in a deep storage chamber in hard

rock. The Validation Test also involved a much more realistic detonation, with the charge located on the chamber floor, and was comprised of a large number of heavy cased munitions. Consequently, an effort to obtain such data was planned as an "add-on" to the scheduled Validation Test. Funding from the SN/MOD to support this work was provided under a U.S. Army-administered Foreign Military Sales case.

The add-on effort included (a) drilling of a vertical, 115-m-long gage hole from the test chamber to the ground surface, (b) installation of ground shock gages (accelerometers) in the gage hole up to a height of 32 m above the chamber, (c) installation of an array of seismic motion gages on the ground surface above the test area, (d) recording and analysis of data obtained by the ground shock and seismic gages, and (e) documentation of the geologic profile along the vertical gage hole and the surface profile along the seismic gage array.

Unfortunately, the on-site contractor experienced severe problems in the initial efforts to drill the vertical gage hole upward from the test chamber. In early 1996, these problems continued until it became clear that continued efforts would cause an unacceptable delay in the performance of the Validation Test. Consequently, it was decided to discontinue the drilling and proceed with the Validation Test without the add-on instrumentation. Instead, a new test, designed specifically for the ground shock instrumentation objective, was scheduled to follow the UAST Validation Test. Named the 1996 Singapore Ground Shock Test, the new experiment would also allow selection of an explosive charge weight more suitable to the Singapore magazine concept. A charge weight of 696 kg was selected to provide a chamber loading density of  $10 \text{ kg/m}^3$ .

Following the completion of the Validation Test in April 1996, the drilling of the vertical gage hole was resumed and completed in May 1996. The required gages were emplaced, and the Singapore Ground Shock Test was conducted in June 1996. This report provides details of the test design, operations, and results.

## Objectives

The primary objective of the Singapore Ground Shock Test was to document the ground shock and surface motions produced by a simulated accidental detonation of munitions in an underground storage chamber, at a nominal loading density of  $10 \text{ kg/m}^3$ . A secondary objective was to record the airblast levels produced in connected tunnels and beyond the tunnel portal.

## Test Site Location and Geology

The underground test area was located within the Linchburg Mine in Socorro County, NM, in Section 7, Township 3S, Range 3W. The location is about 9.6 km southwest of the small town of Magdalena, NM. The Linchburg Mine consists of underground workings on four patented mining claims within the Magdalena Mining District of New Mexico. The mine was operated primarily for the recovery of lead and zinc, and was active until 1972 when, for economic reasons, it was closed. It is currently in a caretaker status.

The Linchburg Mine is located on the north end of the Magdalena Uplift, a horst block tectonic feature within the Rio Grande Rift/Depression. The Magdalena Mountain Range, approximately 39-km long and 16-km wide, is the topographic expression of the Magdalena Uplift. Maximum relief within the range is approximately 1100 m, and the maximum elevation is 3050 m. The Linchburg Mine lies on the western slope of the Magdalena Range, at an elevation of 454 m.

Rocks exposed in the region range in age from Precambrian to Quaternary. The majority of the exposures above the base of the Magdalena Range consist of Paleozoic marine sediments ranging in age from Pennsylvanian to Permian, with Tertiary intrusive and extrusive igneous rock. Most of the Linchburg Mine workings are located in the Mississippian Kelly Limestone, where large replacement bodies of sulfide ore developed adjacent to the major faults. This project was located in an interval of the Kelly Limestone lying between 215 and 275 m from the mine portal. This particular interval is known as the Upper Kelly Limestone, and, at the location of the test area, is 12-m to 15-m thick.

Core samples of the Upper Kelly Limestone were taken during the FY 94 test program, and 13 samples were selected for laboratory testing. Laboratory test results on the cores (Martin 1994) show that the Upper Kelly formation is a coarse-grained, dense limestone, with a mineralogy that is predominantly calcite and quartz. The average dry bulk density is 2.69 g/cc. Laboratory ultrasonic velocity determinations showed an average P-wave velocity of 5400 m/sec ( $\pm 300$  m/sec), and an average S-wave velocity of 3200 m/sec ( $\pm 300$  m/sec). The average compressive strength was 100 MPa ( $\pm 30$  MPa).

Figure 1 is a plan view of the Linchburg Mine in the vicinity of the test area. Two test drifts and seven test chambers were excavated as part of the 1994 UAST program. Two of these rooms, Chambers 1 and 2m were still structurally sound after the 1994 test program, and were modified for the FY96 test program.

An approximate geologic profile of the media penetrated by the vertical gage hole drilled from Chamber 2 is shown in Figure 2. Rock cores were obtained for the lower 34 m of the gage hole. Because of the original time constraints on completion of the drilling, a roller bit was used rather than a slower core barrel bit above 34 m. The geologic profile was developed from the cores, chip samples (produced by the roller bit), and notations made during the drilling process. Briefly, the profile shows limestone to a height of about 24 m above the chamber, overlain by a 9 m layer of shale, then 12 m of limestone with intermittent beds of marine sediments. The upper 65 m was limestone, with intrusive quartz near the ground surface. A refraction seismic survey showed seismic velocities at 12 to 18 m below ground surface to be less than 1200 m/sec, indicating a highly weathered or fractured material (see Chapter 3, Surface Motions). Original plans for this effort had called for an uphole seismic survey and borehole camera survey. However, drilling difficulties, and consequent placement of steel casing and a 51-mm-diameter PVC pipe in the upper portions of the borehole to maintain hole integrity, precluded these measures.

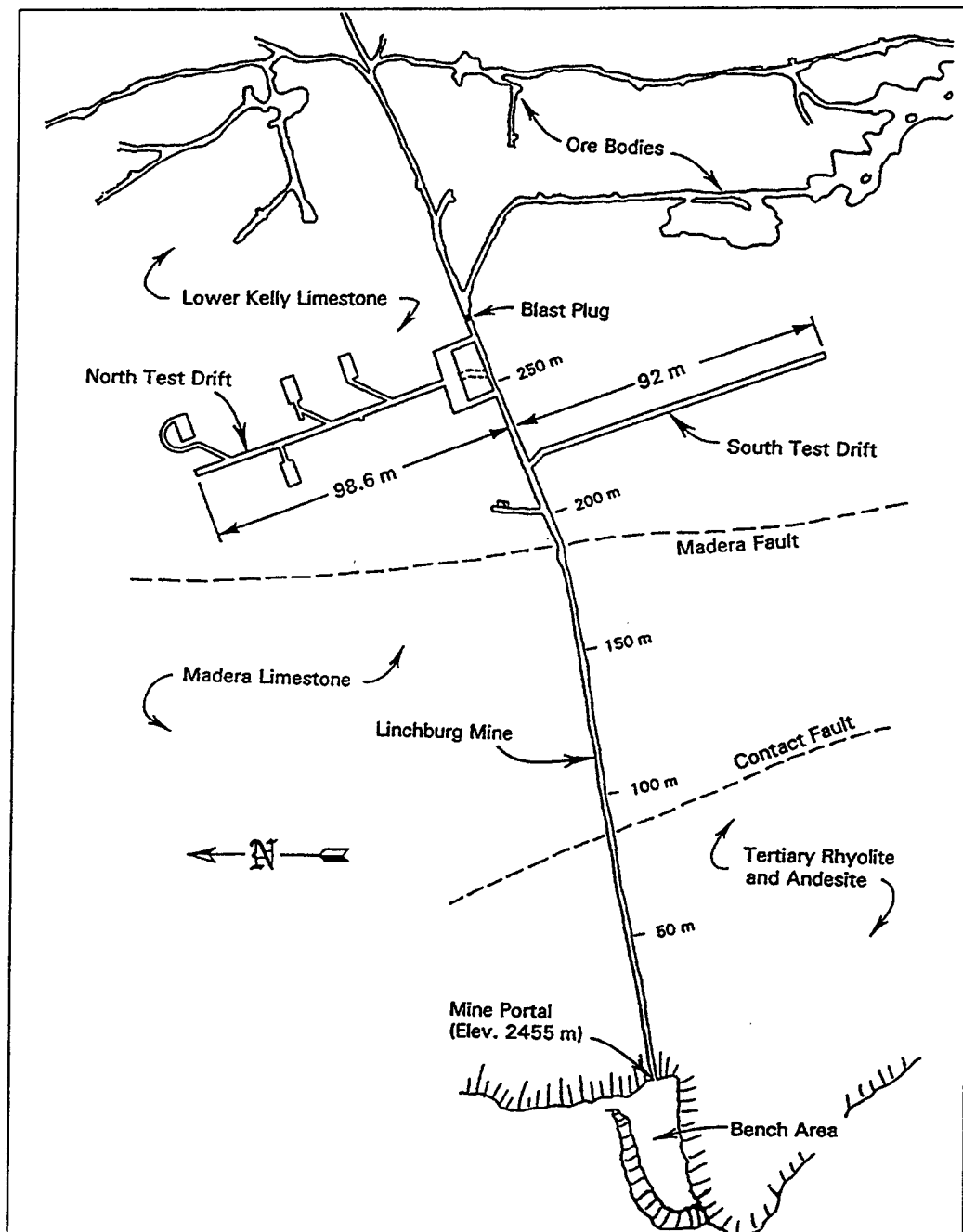


Figure 1. Layout of test drifts and chambers in Linchburg Mine for 1/3-scale underground magazine blast effects tests

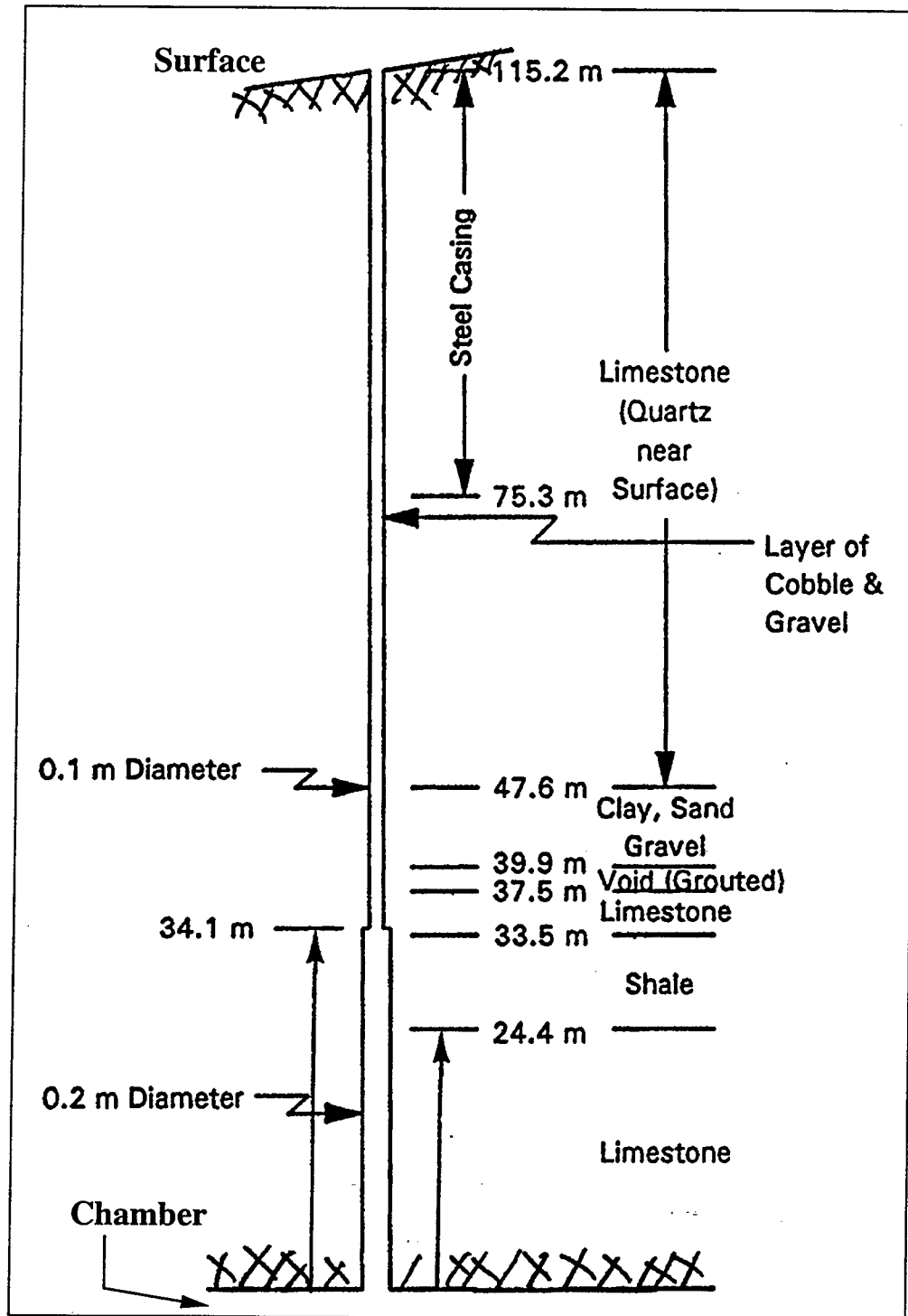


Figure 2. Approximate geologic profile for vertical gage hole above Chamber 2

## 2 Procedure

---

### Test Description

The Singapore Ground Shock Test was conducted in Chamber 2 of the North Test Drift in the Lynchburg Mine. The chambers and tunnels of the North Test Drift were all constructed as idealized, one-third scale simulations of those in a full-scale ammunition storage facility. The explosive charge was placed in the horizontal geometric center of the chamber. For this test, the charge was placed on the chamber floor, in contrast to most of the 1994 tests, where the charges were also centered vertically. The explosive charge consisted of 696 kg of Composition B (Comp B) explosive, which gave a chamber loading density of  $10 \text{ g/m}^3$ .

Because of the extreme fire hazard conditions existing in southern New Mexico at the time of the Singapore Ground Shock Test, steps were taken to minimize the chance of burning detonation products being emitted from the Lynchburg Mine portal. To accomplish this, a sandbag and rock-rubble barrier was placed just inside the test chamber (see Figure 3). The purpose was to reduce the initial surge of blast pressure and detonation products into the tunnel. In addition, the dispersion of the sand into the blast flow was intended to absorb heat energy from the detonation products. A sandbag wall (two bags thick) was built along the three exposed sides of the barrier to a height of 1 m, and the interior was filled with rock rubble. Sandbags were placed on top of this, completing the 1.5-m high barrier.

### Chamber and Tunnel Dimensions

Figure 4 shows the plan and elevation views of the test chamber. The chamber was an elongated trapezoid 8.5-m long on the shortest side, 10.8-m long on the long side, 4-m wide, and 2-m high. The total chamber volume was  $77.2 \text{ m}^3$ .

The sandbag and rock rubble barrier was also trapezoidal in shape and occupied a volume of  $7 \text{ m}^3$ , yielding a net chamber volume of  $70.2 \text{ m}^3$ . The access tunnel leading into Chamber 2 from the North Test Drift was 1.35-m wide and 1.5-m high, and consisted of two sections, one 9-m long leaving the North Test Drift at a  $45^\circ$  angle, and one 6.7-m long leading into the chamber itself.



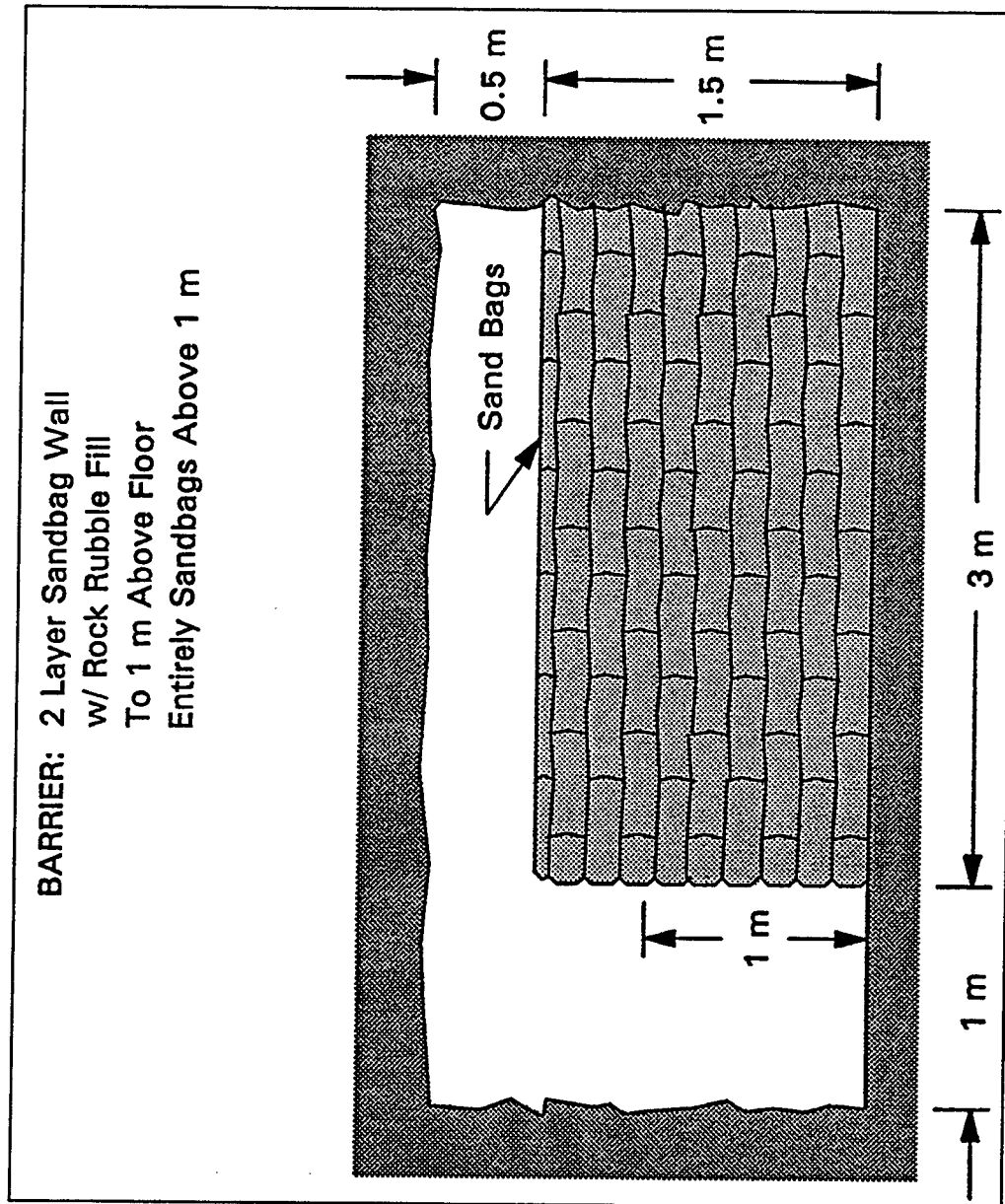


Figure 3. Front view of sandbag and rock rubble barrier inside the entrance to Chamber 2



**Figure 4. Configuration and dimensions of test chamber (Chamber 2)**

## Explosive Charge

The explosive charge for the Singapore Ground Shock Test was constructed of M-15 mines, 155-mm projectiles, and cast Composition B cubes to simulate actual ammunition storage materials. A total of 28 M-15 mines were closely stacked on edge in a two-level horizontal array, with two rows of seven mines per level. Each mine contained 10.34 kg of Composition B. Three pallets of 155-mm M107 artillery rounds were placed at the sides and rear of the charge. Each pallet contained eight projectiles, and each projectile contained 7.1 kg of Composition B. Sixteen cubes of cast Composition B were placed on top of the mines. Each cube was 0.2 m on a side, and contained 14.32 kg of Composition B. Initiator and booster explosives totaled 6.6 kg of C-6 Detasheet and 1.1 kg of C-4, respectively. The total explosive weight was 696.6 kg. The layout of the explosive charge is shown in Figure 5 (plan and profile). The exact chamber loading density was  $9.92 \text{ kg/m}^3$ .

The explosive charge was initiated with a Reynolds FS-42 firing system. A Reynolds RP-83 electric bridge wire (EBW) detonator was attached to a 300-m length of non-electric initiation cord (Nonel). Each test was dual-initiated with two EBW's and two Nonel lines. The M-15 mines were arrayed in horizontal columns (top to base). A booster charge was taped to the base of each column. The booster charges consisted of two sheets of C-6 detasheet (254-mm square) with a Nonel detonator between them. The leads from the Nonel detonators were tied into a ring main (22-grain primacord) which was connected to two Nonel trunk lines running from the charge to the EBW initiator located outside the Linchburg Mine. Half of the 155-mm projectiles (four in each pallet) were initiated with a 0.114-kg C-4 booster charge and a Nonel detonator.

## Instrumentation: Plan and Procedures

### General

The primary purpose of the Singapore Ground Shock Test was to investigate the magnitude and characteristics of seismic-type motions produced on the ground surface above a (simulated) explosion of munitions in an underground storage chamber in rock. Ideally, it would have been desirable to record ground shock and motions over the entire range, from the source to surface locations some distance away. Because of the depth of the test chamber at Magdalena, the rugged surface topography, and other factors, such an effort was not feasible.

Instead, the measurements were concentrated at the two ends of the shock transmission path. An array of gages was installed above the test chamber to record the level of shock energy coupled into the rock surrounding the detonation (i.e., the input), and an array of surface seismic gages was installed on the surface in the area above the detonation to record the resulting surface motions (i.e., output). Airblast measurements were also made in the tunnel system leading from the detonation chamber to ensure that a complete, high-order detonation occurred.

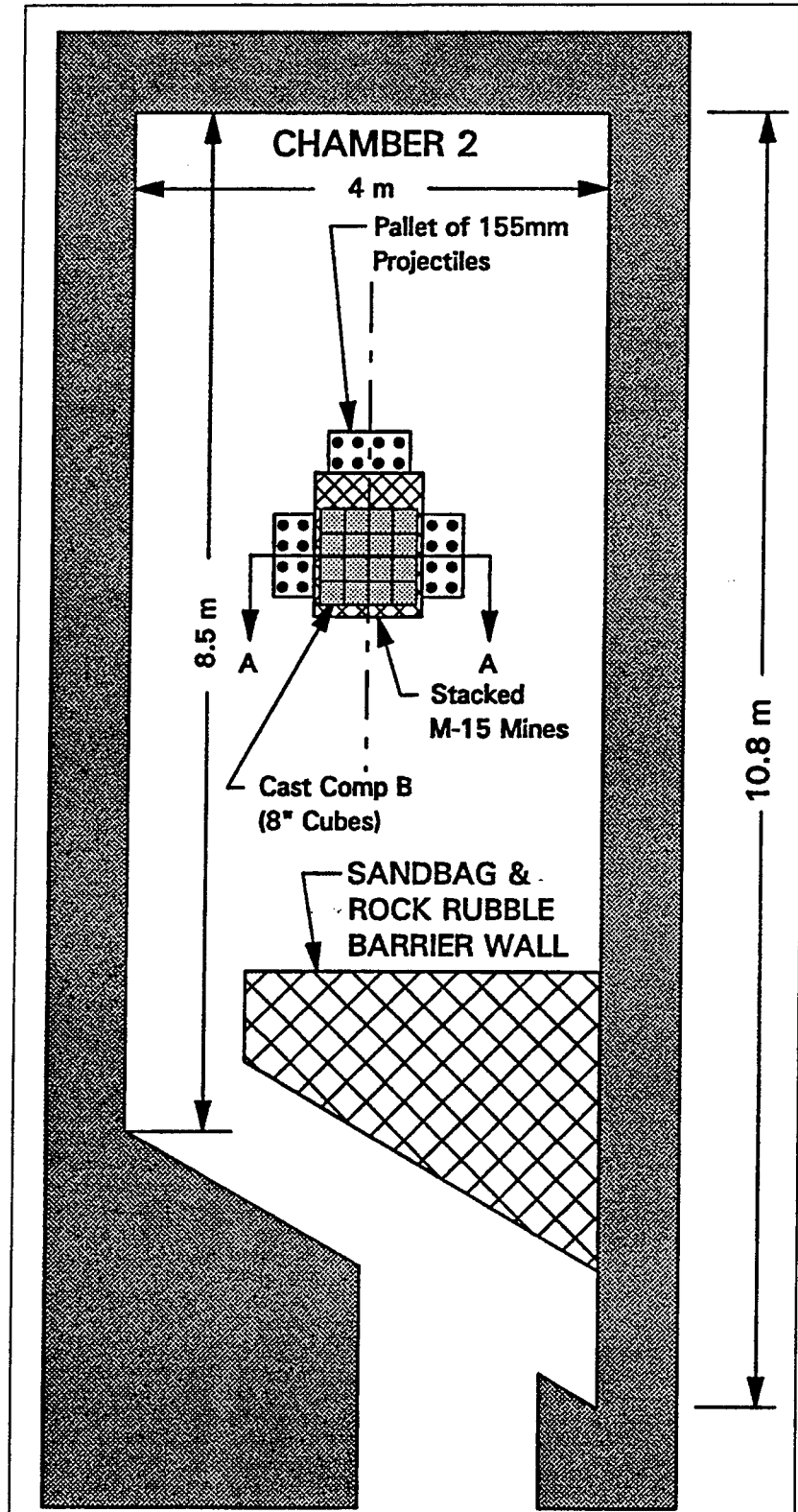


Figure 5. Explosive charge design for Singapore Ground Shock Test

## **Ground shock measurements**

Vertical ground shock accelerations were measured at distances of 4, 8, 15, and 32 m directly above the center of the test chamber. Two gages were installed at each location to confirm the accuracy and reproducibility of the measurements. A 200-mm-diameter hole was required to accommodate the gage canisters.

To ensure that the gage hole was centered above the chamber, it was necessary to drill from the chamber upward. The 200-mm-diameter hole extended to the 32-m height of the uppermost gage location. A 100-mm-diameter hole was drilled from that point to the ground surface, some 115 m above the chamber (see Figure 6).

The gage canisters were attached to a narrow "sled" of PVC pipe to keep them in their proper position and vertical alignment. The gage cables were first lifted up the 115-m hole height, and the sled was then assembled in the test chamber in 2-m sections and pulled up into the 200-mm hole. After checking to make sure each gage was operational, the bottom of the hole was sealed, and a rock-matching grout was pumped into the hole in lifts through the PVC pipes of the sled.

## **Surface motion measurements**

Seismic gages were installed along the ground surface by FC/DTRA, to record the surface motions. The array consisted of six stations ranging in location from the top of the ground shock gage hole (approximately directly above the chamber) to a distance of 154 m to the southeast. A remote array of four stations was located 1 to 2 km from the test area. Three gages were installed at each location to provide triaxial measurements, i.e., vertical, horizontal, along the north-south axis, and horizontal along the east-west axis. Figure 7 shows the layout of the surface motion gage stations.

## **Airblast measurements**

A total of 15 side-on overpressure gages, emplaced flush with the floor of the North Test Drift and Linchburg Mine tunnel, were used to record the pressure-time histories of the airblast shock wave and as flow produced by the detonation of the explosive charge for the Singapore Ground Shock Test. The gage locations are shown in Figure 8.

# **Instrumentation: Transducers**

## **Ground shock gages**

All free-field ground shock measurements were made with Endevco Corporation Model 2262CA and 7270A accelerometers. Both models are piezoresistive types with the active elements used in a bridge configuration. The

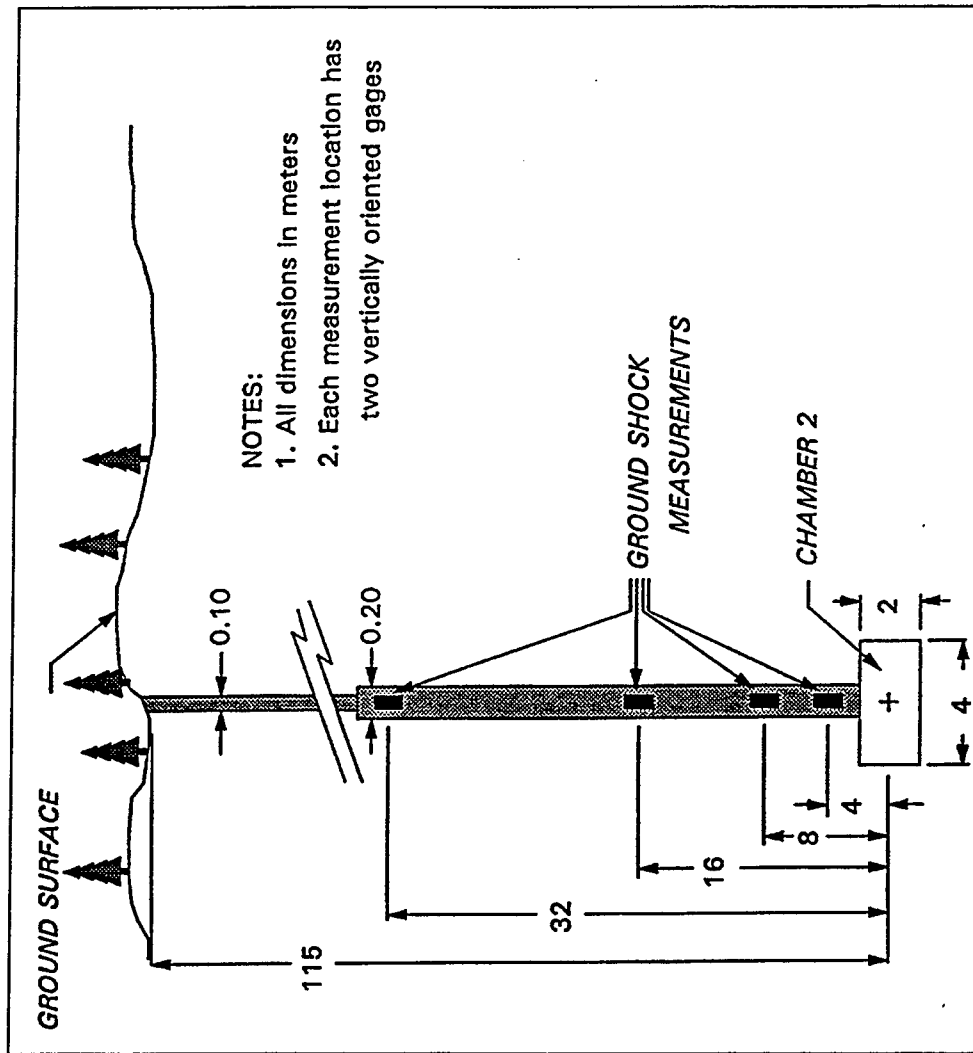


Figure 6. Ground shock measurements locations in vertical gage hole for Singapore Ground Shock Test

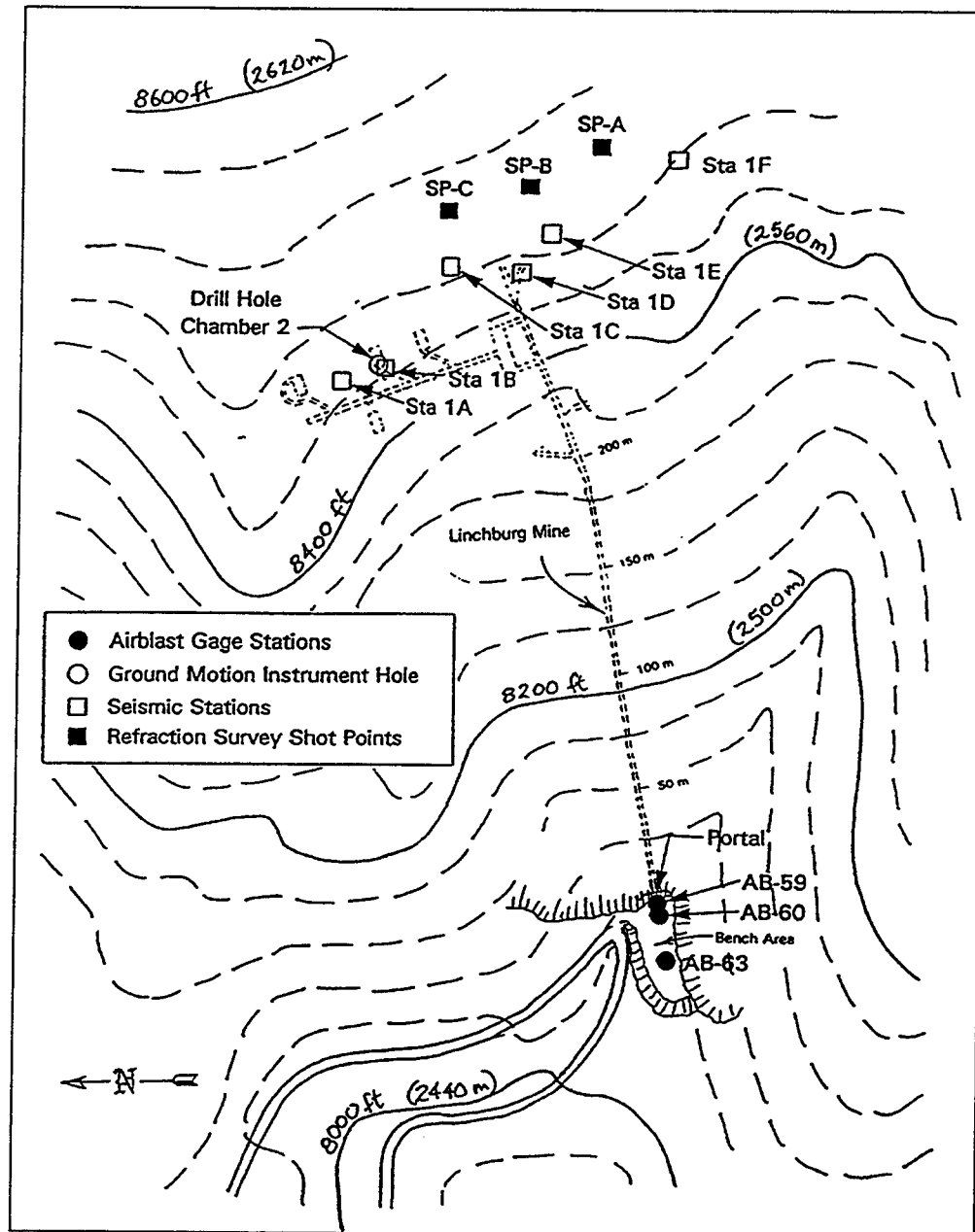


Figure 7. Seismic sensor and shot point layout on overburden surface above the Linchburg Mine, Singapore Ground Shock Test

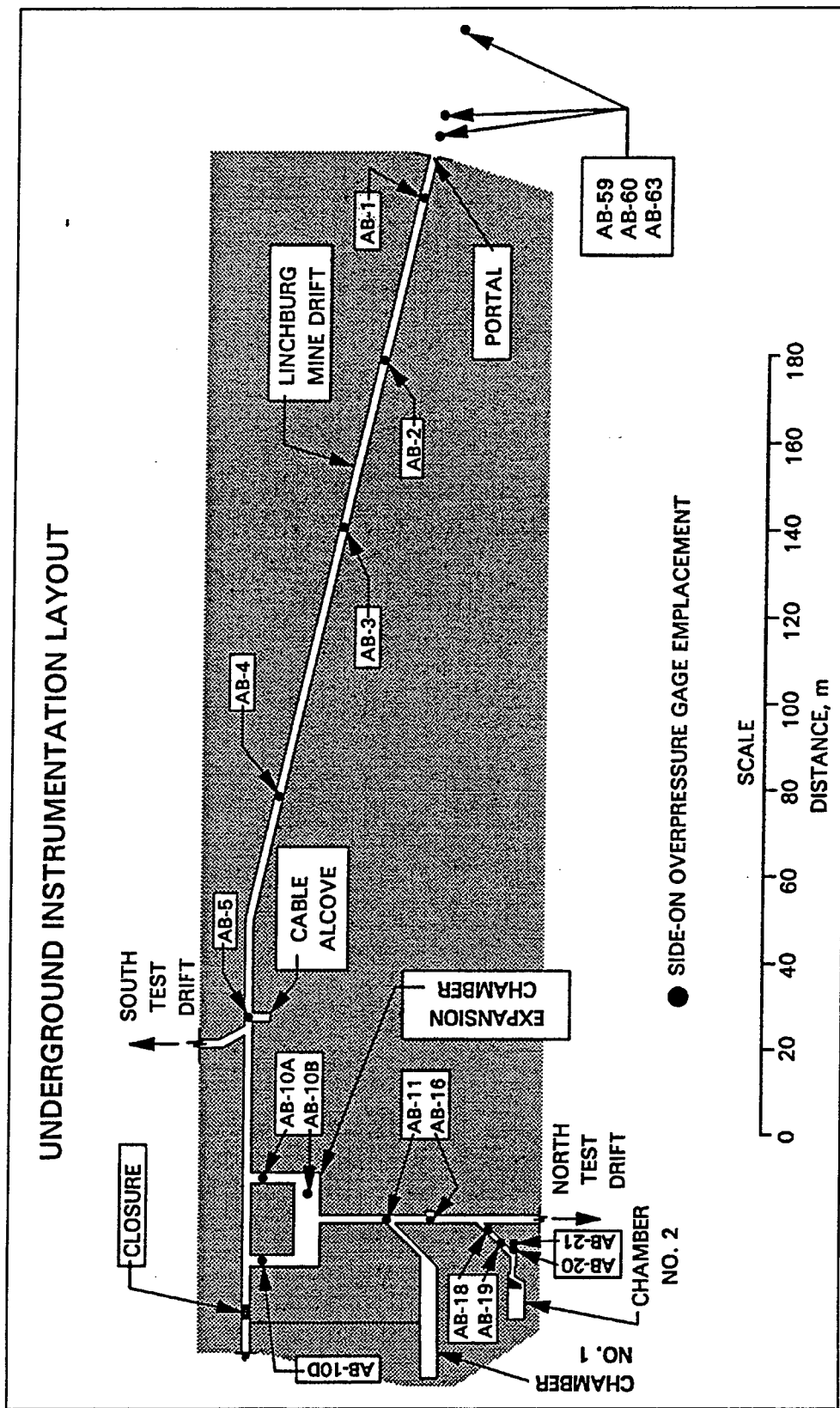


Figure 8. Airblast gage layout for Singapore Ground Shock Test



Model 2262CA is a fluid-damped (0.707 critical) device manufactured in ranges of 25 to 2,000 g's. Frequency responses vary from 0 to 650 Hz for the 25-g gage up to 0 to 3,000 Hz for the 2,000-g gage. The Model 2262CA was used in positions where acceleration was expected up to about 1,000 g's. The Model 7270A is a miniature, undamped gage manufactured in ranges of 2,000 to 200,000 g's. Frequency responses vary from 0 to 10 kHz for the 2,000-g gage to 0 to 150 kHz for the 200,000-g gage. The Model 7270A was used at positions where acceleration levels were expected to be above 1,000 g's. All free-field gages were oriented radially, i.e., with the sensing axis of the gages aimed towards the charge center.

### **Surface motion gages and recording system**

All surface ground motion measurements were made with Terra Technology SSA312 accelerometers. These transducers are servo accelerometers with a flat frequency response from 0 to 50 Hz. The sensitivity of these gages is adjustable and was set to one volt per g, which gives a peak-to-peak range of  $\pm 5$  g's. The acceleration data were recorded on digital Refraction Technology 71 A-07 36-channel units, with a dynamic range of 24-bits and an input range of  $\pm 10$  volts. The recorder was operated at 500 samples per second. These recorders have an initial anti-alias filter, which was set at about 4/5 of the Nyquist folding frequency, so that the upper limit of response was about 200 Hz and the system response was flat down to DC. Recorders were set to turn on a coupled of minutes prior to the anticipated shot time, with a total record length of 5 minutes. Timing was provided by an internal clock, which was corrected to GPS satellite time each second.

### **Airblast gages**

Airblast measurements were made using Kulite Semiconductor Products Model HKS-375 pressure gages. These units are piezoresistive bridge transducers, and are manufactured in ranges of 3.45 to 206 MPa. The natural frequencies are very high, ranging from 350 kHz for the 3.45-MPa gage up to 725 Hz for the 206-MPa gage.

## **Instrumentation: Protection Systems**

### **Accelerometer canisters**

The ground shock accelerometers were mounted in aluminum canisters to provide physical protection and solid mounting platforms. The cylindrical canisters were 101.6 mm in diameter and 76.2 mm long with a 19-mm wall thickness.

### **Airblast gage housings**

The HKS airblast gages were mounted in steel housings, and were protected from fragments and other debris by a debris shield. The debris shield, known as

the "8-hole debris shield," consists of two steel disks; one contains the airblast gage threaded mount, and the other provides a ported cavity. The porting system consists of eight small holes drilled through the disk. Details of both disks are shown in Figure 9. The airblast porting holes are 1.4 mm in diameter and 4.74 mm in length. Previous test data indicates that this shield should allow for airblast rise times on the order of 200 microseconds.

### **Cable and cable protection**

Two types of signal cables were used for instrumentation connections. Both types are shielded, twisted-pair instrumentation cables. The first type, designated "small cable," is a 4-conductor shielded cable 3.12 mm in diameter. Individual conductors are #28 AWG, with polyethylene jackets. Shielding is 0.025-mm polyester/aluminum tape providing 100% coverage, with four #28 AWG drain wires. The outer jacket is PVC. Conductor resistance is 22.9 ohms/100 m. Capacitances are 75 pF/m (conductor-to-conductor) and 141 pF/m (conductor-to-shield). The second cable type, designated as "large" cable, is a 4-conductor shielded cable 6.45 mm in diameter. Individual conductors are #22 AWG, with polyethylene jackets. Shielding is provided by #34 AWG copper wire braid giving 90% coverage. The outer jacket is PVC. Conductor resistance is 4.5 ohms/100 m. Capacitances are 65 pF/m (conductor-to-conductor) and 114 pF/m (conductor-to-shield).

Large cable was used for the main cable runs, which extended from the instrumentation recording van to two junction box (J-box) locations; one inside the Linchburg mine (for airblast gages) and another at the top of the vertical gage hole, directly above the test chamber. Gage-to-J-box cable for the underground airblast locations was the small cable. Uphole cable for the ground shock accelerometers was the small cable to a point 34 m above the chamber (where the gage hole diameter reduced from 0.2 m to 0.1 m), then, a splice to the larger cable was made.

At all locations where large stresses, rock fracturing, or high velocity fragments was a potential problem, the small cable was run through 6.35-mm-diameter stainless steel tubing for protection. This protection was used for all the small cabling in the vertical gage hole.

### **Grouting**

The vertical gage hole for the ground shock measurements was filled with the same grout developed for and used on the 1994 Magdalena tests. The requirements for the grout design were, in order of decreasing importance: pumpability, density (target = 2646 kg/m<sup>3</sup>), compressive strength (target > 69 MPa), and P-wave velocity (target = 4570 m/sec to 5490 m/sec). Tests of grout samples after the 1994 series showed a density of 2522 kg/m<sup>3</sup>, compressive strength of 26.6 MPa, and P-wave velocity of 3129 m/sec. Pumpability of this mix was good, and the density was close to the target density. Compressive strengths

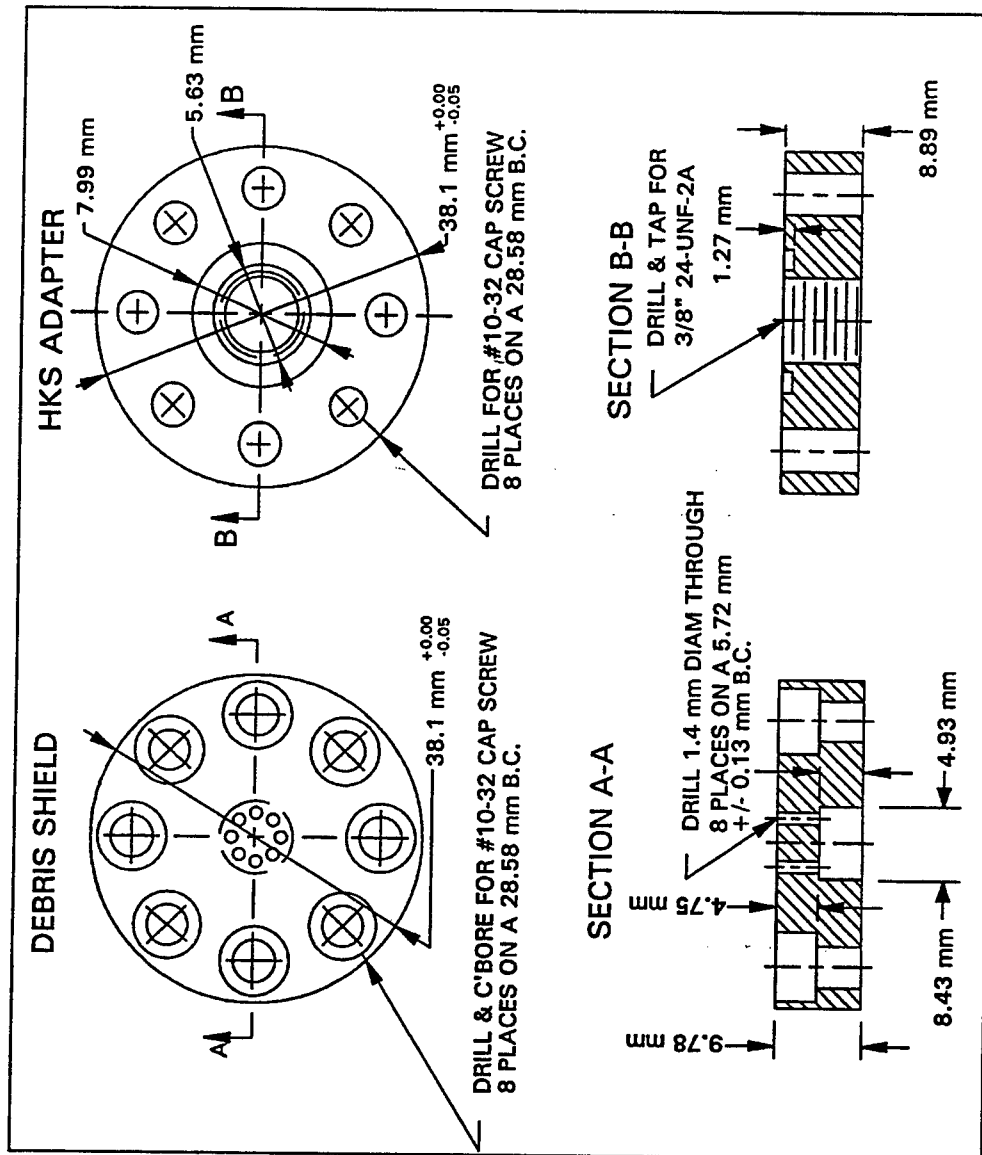


Figure 9. Airblast gage debris shield

and P-wave velocities were less than the target values, averaging 39 percent and 68 percent of the target values, respectively. The grout sample properties are given in Table 1.

## **Instrumentation: Data Recording**

### **Recording system**

Data processing and recording equipment was housed in an instrumentation trailer located about 200 m north of the Linchburg Mine portal. All electronic data were processed through WES Model 103-D differential amplifier/signal conditioning systems. Shunt resistor calibration was applied to each channel immediately prior to the test. Data signals were recorded on Pacific Model 9830 transient data recorders. These units utilize 14 memory segments, each capable of storing 8192 data points. Sample rates can be programmed individually for each memory segment. Ground shock data were recorded at a rate of 4 microseconds per sample for all 14-memory segments, giving a total recording time of 458 milliseconds. Airblast data sampling used individually programmed rates for each memory segment. The first six segments were sampled at four microseconds per sample. The next eight segments were sampled at decreasing rates of 8, 16, 32, 64, 128, 256, 512, and 1024 microseconds per sample, respectively, to give a total recording time of 16.9 seconds.

### **Predictions for gage ranging**

Airblast gage ranging for the Singapore Ground Shock Test was based on predictions computed with BLASTX (Version 3.5) computer code. BLASTX 3.5 contains recent modifications for predicting the airblast effects from detonations of large explosive charges in small rooms, analogous to underground storage magazines with moderate to large chamber loading densities.

Ground shock predictions for the Singapore Ground Shock Test were made using empirical methods drawn from the 1994 test program. Motion data from the 1994 tests were noted to be very nearly independent of the explosive loading density, expressed in terms of  $\text{kg/m}^3$ . Instead, motions were noted to scale with the cube root of the charge weight.

**Table 1.**  
**Results of Grout Sample Properties Tests**

Date Cast (June 96)	Batch No.	Specimen No.	Age (days)	Sonic Pulse Velocity (m/sec)	Dynamic Modulus (GPa)	Density (Mg/m <sup>3</sup> )	Unconfined Compressive Strength (MPa)
10	1	1	8	3,464.6	22.08	2.65	38.69
10	1	2	8	3,441.5	21.50	2.65	38.21
10	1	3					
11	2	4	7	3,433.2	22.10	2.72	37.76
11	2	5	7	3,425.3	22.72	2.72	34.34
11	2	6					
11	4	7	7	3,427.4	21.63	2.70	35.79
11	4	8	7	3,395.1	21.73	2.71	36.48
11	4	9					
12	5	10	6	3,372.6	20.48	2.65	34.10
12	5	11	6	3,387.5	21.30	2.65	33.41
12	5	12					
12	7	13	6	3,358.8	22.34	2.69	30.69
12	7	14	6	3,418.3	20.59	2.68	37.21
12	7	15					

## 3 Results and Discussion

---

### General

The Singapore Ground Shock Test was detonated at 1400 hours on 18 June 1996. At shot time, all airblast and ground shock gage channels were active (although one accelerometer, Gage 332B, was noisy and unstable). All recording equipment operated as programmed. A high-order detonation was achieved, and substantial dust and very small debris exited the tunnel portal. No flame was evident at the portal.

A crater measuring approximately 0.5-m deep and 4 m in diameter was formed in the floor of the test chamber, beneath the charge position (Figure 10). No other damage to the chamber or access tunnel was noted, other than small chips in the rock surfaces from fragment impacts. The sandbag/rock rubble barrier at the front of the chamber was completely blown away. Most of the debris was deposited in the debris trap in front of the chamber entrance.

### Free-Field Ground Shock Measurements

#### Instrument performance

Five of the eight free-field accelerometers installed yielded excellent data. Two gages that failed to provide good data were in the uppermost canister, at a range of 32 m from the chamber center. One of these (Gage 332B), as mentioned above, had been producing noisy and unstable outputs prior to the test, and its failure can be attributed to gage or cable damage. The other (Gage 332A) produced a freely oscillating signal at about 150 Hz, which was almost certainly due to failure of the grout to completely envelope the canister, allowing it to vibrate, or "rattle," in the borehole. This problem was not unexpected, due to problems encountered in pumping the grout to such a height through the small-diameter PVC pipe.

The third gage, which failed to produce good data, was Gage 308A. This gage yielded a high-quality signal which showed all the timing and pulse characteristics of Gage 308B; its amplitude, however, was too high by a factor of

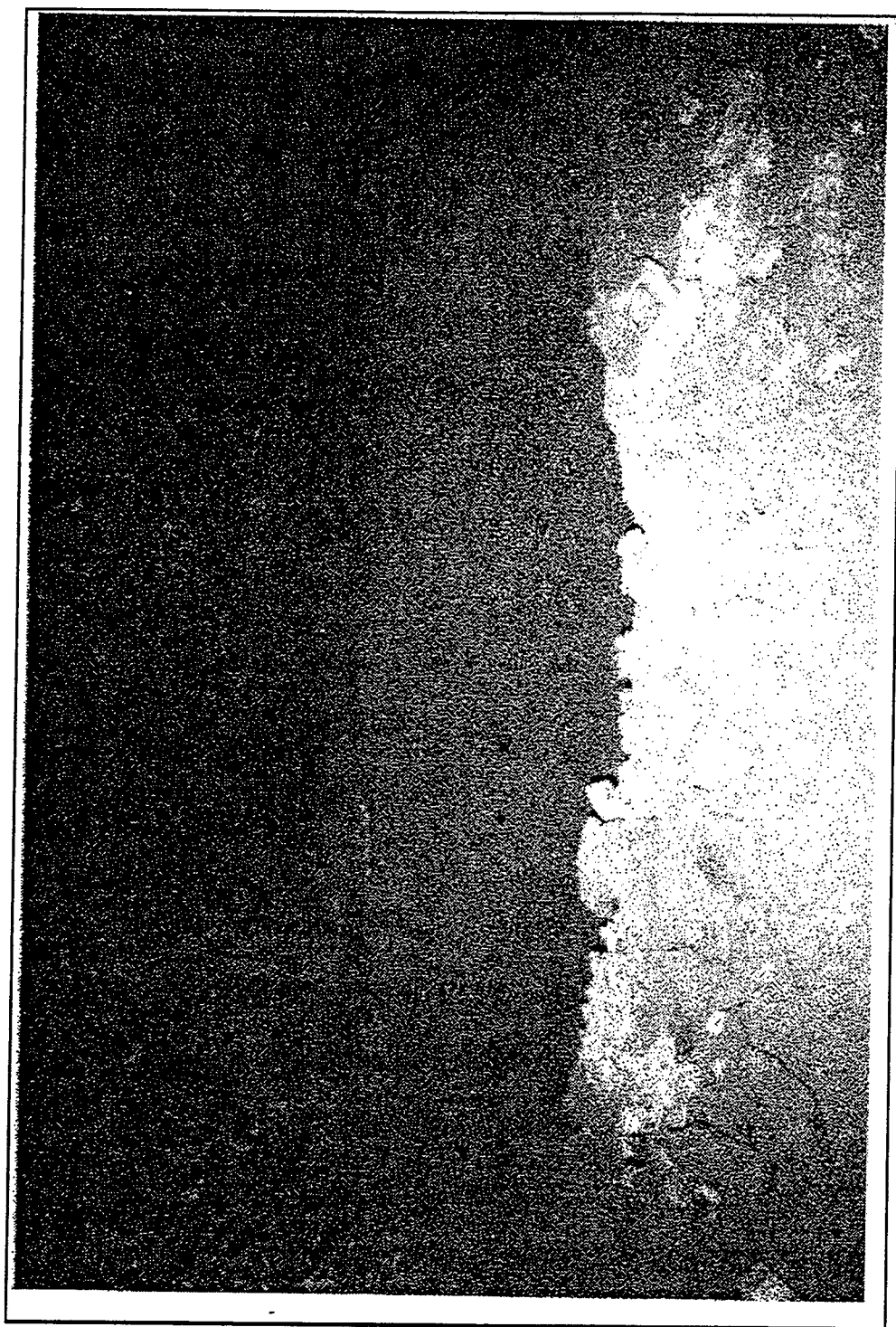


Figure 10. Crater in the floor of Chamber 2 produced by the explosive charge detonated for the Singapore Ground Shock Test

6 to 7. Extensive checks of the calibration records, calibration resistor, amplifier response, amplifier gain, and digital recorder response failed to provide any satisfactory explanation of the problem. It is concluded that, for this gage, an error occurred in calibration or signal amplitude that defies identification and correction.

### Shock arrival times

Data from the free-field ground shock measurements are summarized in Table 2. Time histories, including first and second integrals, are presented to a time of 40 msec in Appendix A. Initial arrival times for the ground shock are plotted versus distance in Figure 11. Propagation velocities were 5,738 msec for the 4- to 8-m interval above the chamber, 4,050 msec for the 8- to 16-m interval, and 3,751 msec for the 16- to 32-m interval. For Test 5 in the 1994 series, which was a test of 14.6 kg/m<sup>3</sup> loading density in Chamber 4 (located about 27 m from Chamber 2), shock arrival times were obtained in a vertical borehole at similar distances. For that test, propagation velocities were 3,636 msec for the 8- to 16-m interval, and 3,641 msec for the 16- to 32-m interval. Insofar as shock propagation velocities may be taken as one index of in-situ rock properties, there appears to be no significant difference in shock propagation velocities in the first 32 m of rock above Chambers 2 and 4.

### Accelerations

Peak accelerations, scaled by the cube-root of the charge yield, are plotted for the five fully successful measurements in Figure 12. Also included for comparison, are data from Tests 2, 3, 5, 6, and 7 of the 1994 UAST series at Magdalena. The UAST events involved charge weights of 72, 344, 943, 2570, and 2890 kg (of Comp B), respectively, representing chamber-loading densities of 1 to 40 kg/m<sup>3</sup>. All of these tests were detonated in Chamber 4 (see Figure 13), and all involved idealized charges (no munitions) aligned along the central axis at mid-height of the chamber. Cube-root scaling collapsed the UAST data quite well, and it is not possible to distinguish the scaled data by test. The results of the Singapore Ground Shock Test are in good agreement with those from the 1994 tests, and are either uniformly high or low with respect to the previous experiments. Also shown on Figure 12 is a least squares curve fitted to the data. The curve has the equation  $A_s = 3100 R_s^{-3.0}$ , where  $A_s$  is the scaled acceleration, and  $R_s$  is the scaled range. The Singapore Ground Shock Test data lies slightly above the fitted curve, but well within the general data scatter.



**Table 2.****Free-Field Ground Shock Data Summary**

Gage No	Range (m)	Scaled Range (m/kg <sup>1/3</sup> )	Arrival Time (msec)	Peak Acceleration (g)	Peak Velocity (m/sec)	Peak Displacement (mm)	Scaled Acceleration (gx/kg <sup>1/3</sup> )
204A	4	0.45	0.484	5400	9.95	4.5	47790
204B	4	0.45	0.453	5183	9.70	4.21	45870
208A	8	0.90	1.15	996	0.95	0.59	8815
208B	8	0.90	1.15	Note (1)	--	--	--
216A	16	1.81	3.11	167.5	0.37	0.50	1482
216B	16	1.81	3.14	145.4	0.35	0.52	1287
232A	32	3.62	7.30	Note (2)	--	--	---
232B	32	3.62	7.39	Note (3)	--	--	--

**Notes:**

- (1) Data amplitude in error; amplitudes not reported.
- (2) Severe signal oscillation at 150 Hz; no amplitudes reported.
- (3) Gage or cable damage; no data recorded.

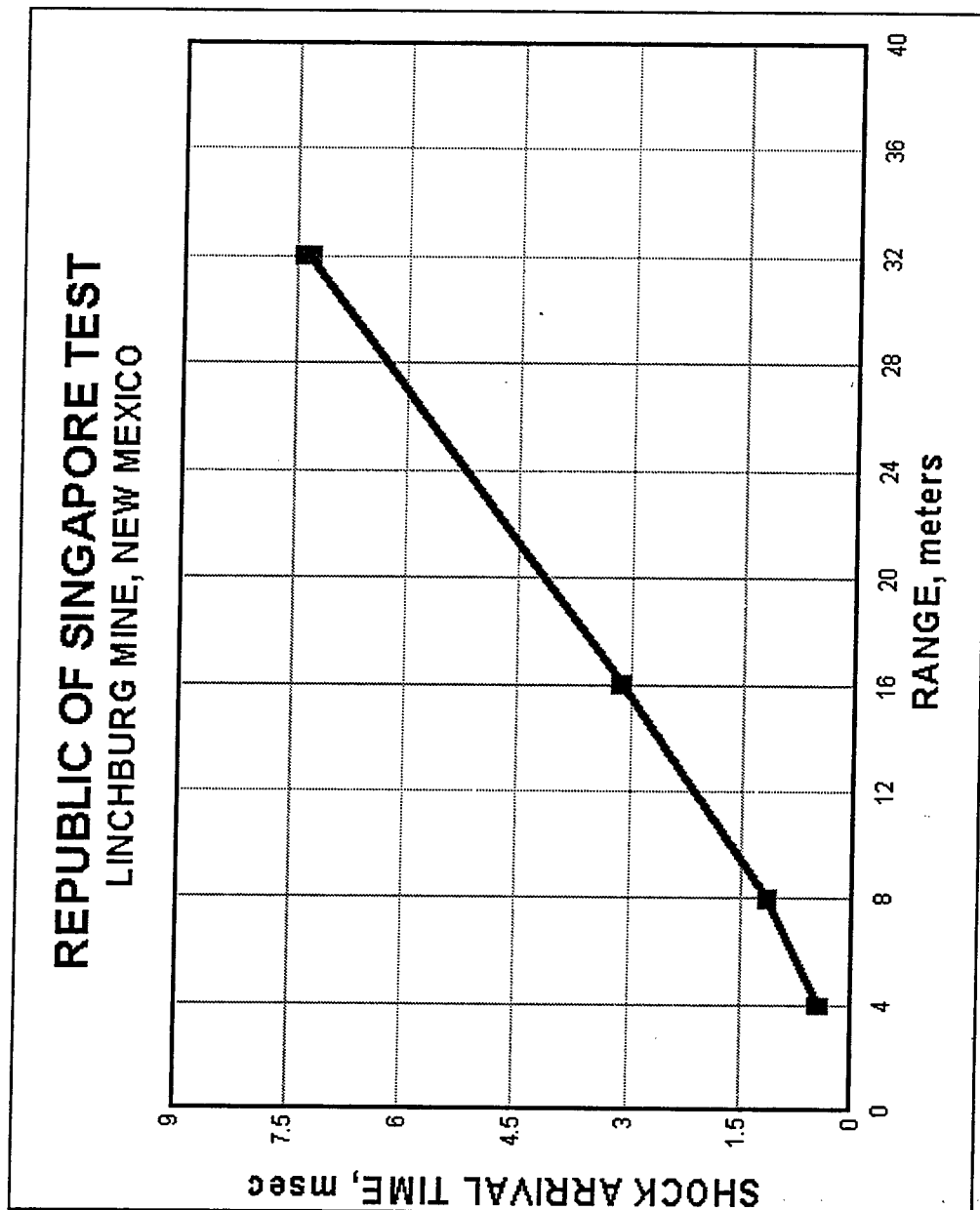


Figure 11. Ground shock arrival times versus range

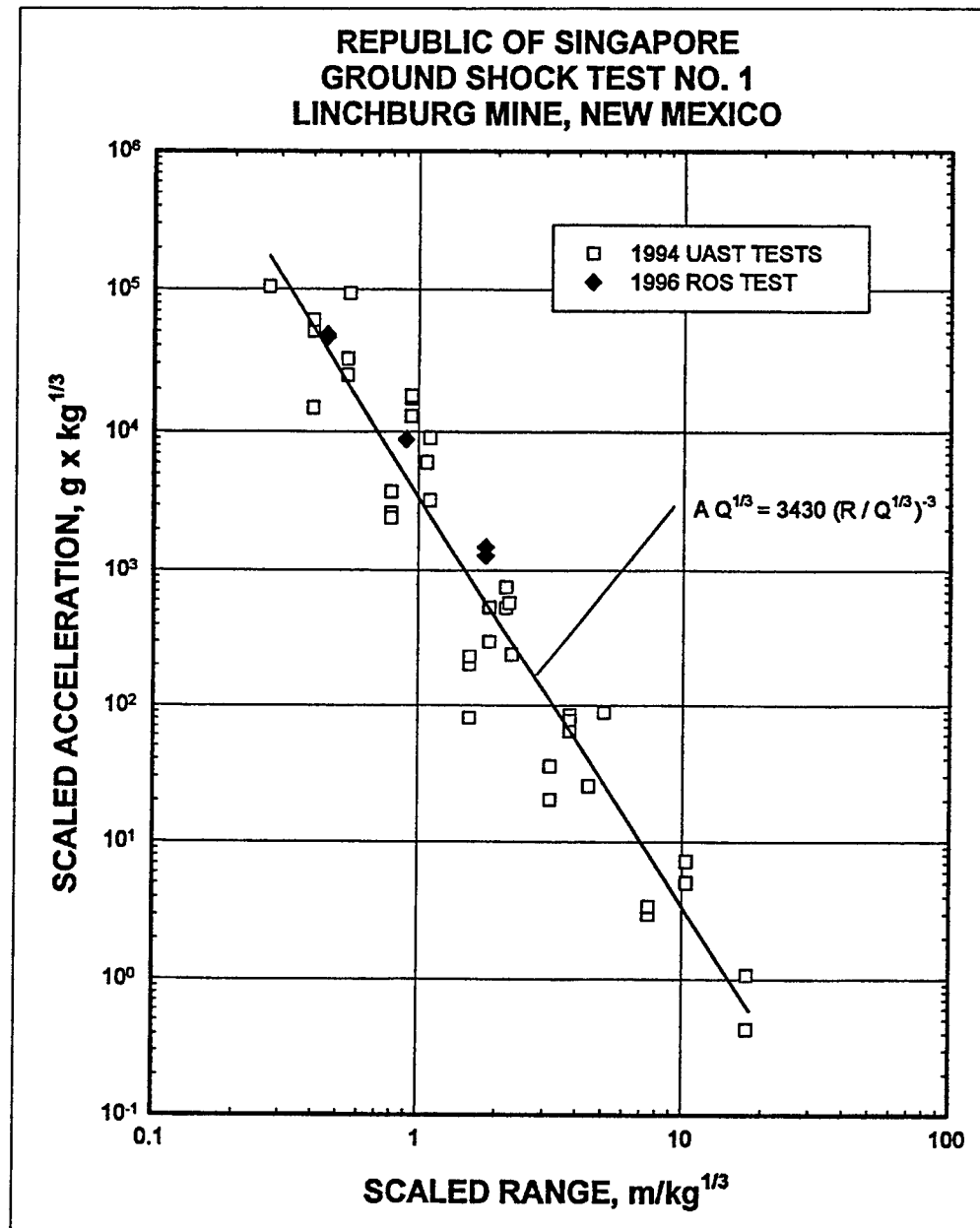


Figure 12. Scaled peak acceleration versus scaled range

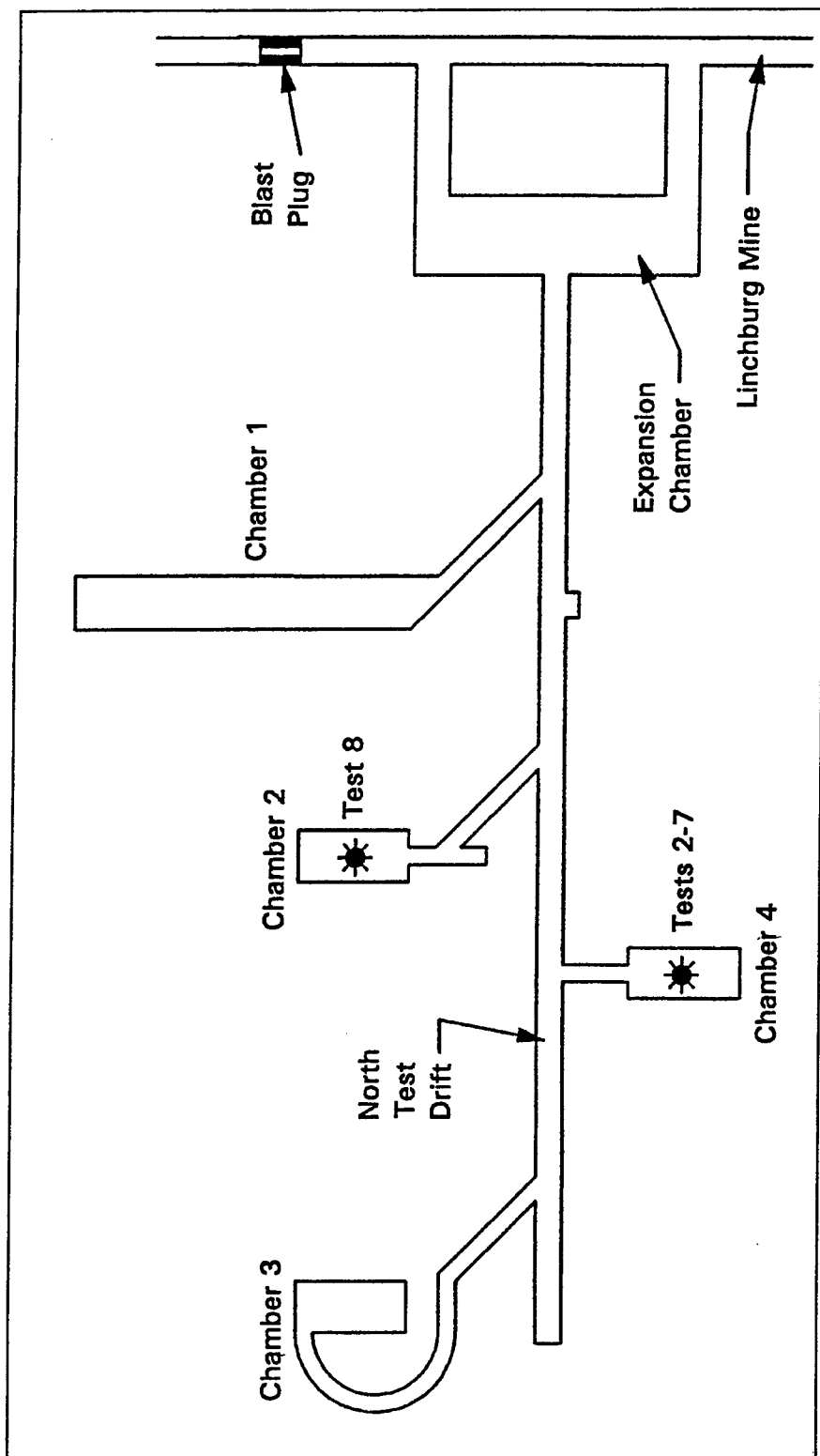


Figure 13. Location of U.S. Phase 3 Intermediate-Scale tests

## Particle velocity

Free-field particle velocities were derived from the acceleration data by numerical integration, and are plotted versus scaled range in Figure 14. The data spread is tighter than was seen for the accelerations, and the data from the Singapore Ground Shock Test are again in excellent agreement with those from the 1994 UAST series. The least squares curve fit has the equation  $U = 1.8 R_s^{-2.5}$ , where  $U$  is the particle velocity and  $R_s$  is the scaled range. The Singapore Ground Shock Test data points fall close to the fitted curve, particularly at the 4 m and 16 m ranges, and are again well within the data scatter.

## Surface Motions

### Near-surface seismic velocity survey

A refraction survey was conducted by FC/DTRA on the surface of the mountain above the test chambers in the Lynchburg Mine. Three shot points, designated as SPA, SPB, and SPC, were positioned along a straight, nearly level line. The locations of these shot points relative to the test chambers in the Lynchburg Mine are shown in Figure 7. The near-surface profile of the overburden inferred from the refraction survey is shown in Figure 15. Three layers were identified: (a) a highly fractured surface layer 3-to 4-m thick, with a seismic velocity of 638.9 m/sec, (b) a second layer ranging to depths of 12- to 17-m below the surface, with a seismic velocity of 1175 m/sec, and (c) a third, deeper layer, with a seismic velocity of 2162 m/sec.

### Accelerations and velocities

Acceleration-time histories recorded by the triaxial seismic gages placed at the ground surface above Chamber 2 were integrated to obtain particle velocity time histories. Stacked plots of these waveforms are presented in Figures 16, 17, and 18 for the vertical, horizontal E-W, and horizontal N-S sensors, respectively. The surface gage locations (horizontal distance and elevation) are given in Table 3. A summary of the peak motions obtained from these gages is given in Table 4.

Peak particle velocity data for the vertical and horizontal E-W gages are plotted versus horizontal distance in Figure 19. The horizontal distances were measured from the top of the ground motion instrument bore hole, which was nearly vertically above the center of Chamber 2. The particle velocity data are also plotted versus slant distance from the center of Chamber 2 in Figure 20. The data plotted in Figures 19 and 20 show similar trends. As the horizontal distance (from the point on the surface directly above the chamber) increases, the dominant motion changes from vertical to horizontal.

In Figure 21, the vertical surface motions (one half of the peak-to-peak vertical velocities plotted in Figures 19 and 20) are compared to the free-field motions

**Table 3.**  
**Locations of Seismic Surface Motion Gages, Refraction Survey Shot**  
**Points, and External Airblast Gages**

Horizontal Coordinates		Elevation (m)	Remarks
X (m)	Y (m)		
1855.9	1523.8	2576.0	Top of Ground Motion Instrument Hole from Chamber 2
1855.7	1505.4	2577.1	Seismic Sensor Station 1A
1852.9	1527.2	2575.2	Seismic Sensor Station 1B
1883.7	1572.8	2586.0	Seismic Sensor Station 1C
1870.1	1599.9	2584.2	Seismic Sensor Station 1D
1880.8	1619.3	2587.3	Seismic Sensor Station 1E
1889.5	1684.7	2584.9	Seismic Sensor Station 1F
1907.2	1655.2	2590.7	Refraction Survey, Shot Point A
1904.0	1617.7	2591.1	Refraction Survey, Shot Point B
1907.1	1580.6	2591.4	Refraction Survey, Shot Point C
1587.0	1552.4	2453.8	WES-Free-Field Airblast Gage (59ABSO)
1582.3	1551.4	2453.8	WES-Free-Field Airblast Gage (60ABSO)
1562.4	1547.3	2453.6	WES-Free-Field Airblast Gage (63ABSO)
Notes: Basis of bearing is arbitrary. Elevation based on Gage 63ABSO at 8050.0 ft msl. Elevation taken by trigonometric leveling, with accuracy of $\pm 0.05\text{m}$ .			

Table 4. Seismic Surface Motion Data Summary

Station No.	Gage Orientation	Arrival Time (msec)	Peak Acceleration (g's)		Peak Particle Velocity (mm/sec)		Peak Displacement (mm)	
			(+)	(-)	(+)	(-)	(+)	(-)
1AC1	Vertical	3402	0.4517	0.5818	11.619	16.688	0.07122	0.03538
1AC2	Horiz (E-W)	3402	0.1623	0.1701	4.795	3.847	--	--
1AC3	Horiz (N-S)	3402	0.2353	0.2013	6.684	6.364	--	--
1BC1	Vertical	3402	0.2265	0.2842	8.690	9.528	0.08123	0.00275
1BC2	Horiz (E-W)	3408	0.1633	0.1531	3.944	5.435	--	--
1BC3	Horiz (N-S)	3404	0.0661	0.0689	3.688	2.530	0.02251	0.01864
1CC1	Vertical	3406	0.1773	0.1759	4.544	6.224	0.02873	0.01143
1CC2	Horiz (E-W)	3410	0.0840	0.0889	2.740	2.966	0.01354	0.02034
1CC3	Horiz (N-S)	3408	0.0720	0.0687	1.540	2.396	0.01034	0.01204
1DC2	Horiz (E-W)	3410	0.1161	0.0923	2.408	1.882	0.01958	0.01605
1DC3	Horiz (N-S)	3412	0.1201	0.0980	2.654	2.052	--	--
1EC1	Vertical	3412	0.0115	0.1294	2.940	4.380	0.01773	0.01052
1EC2	Horiz (E-W)	3414	0.1509	0.1182	5.596	3.569	0.02118	0.01961
1EC3	Horiz (N-S)	3414	0.1297	0.1089	3.581	3.301	--	--
1FC1	Vertical	3422	0.0518	0.0464	1.318	1.767	0.00953	0.00528
1FC2	Horiz (E-W)	3424	0.0583	0.0509	1.522	1.419	0.00887	0.00889
1FC3	Horiz (N-S)	3426	0.0795	0.0646	2.032	1.772	0.01154	0.00675

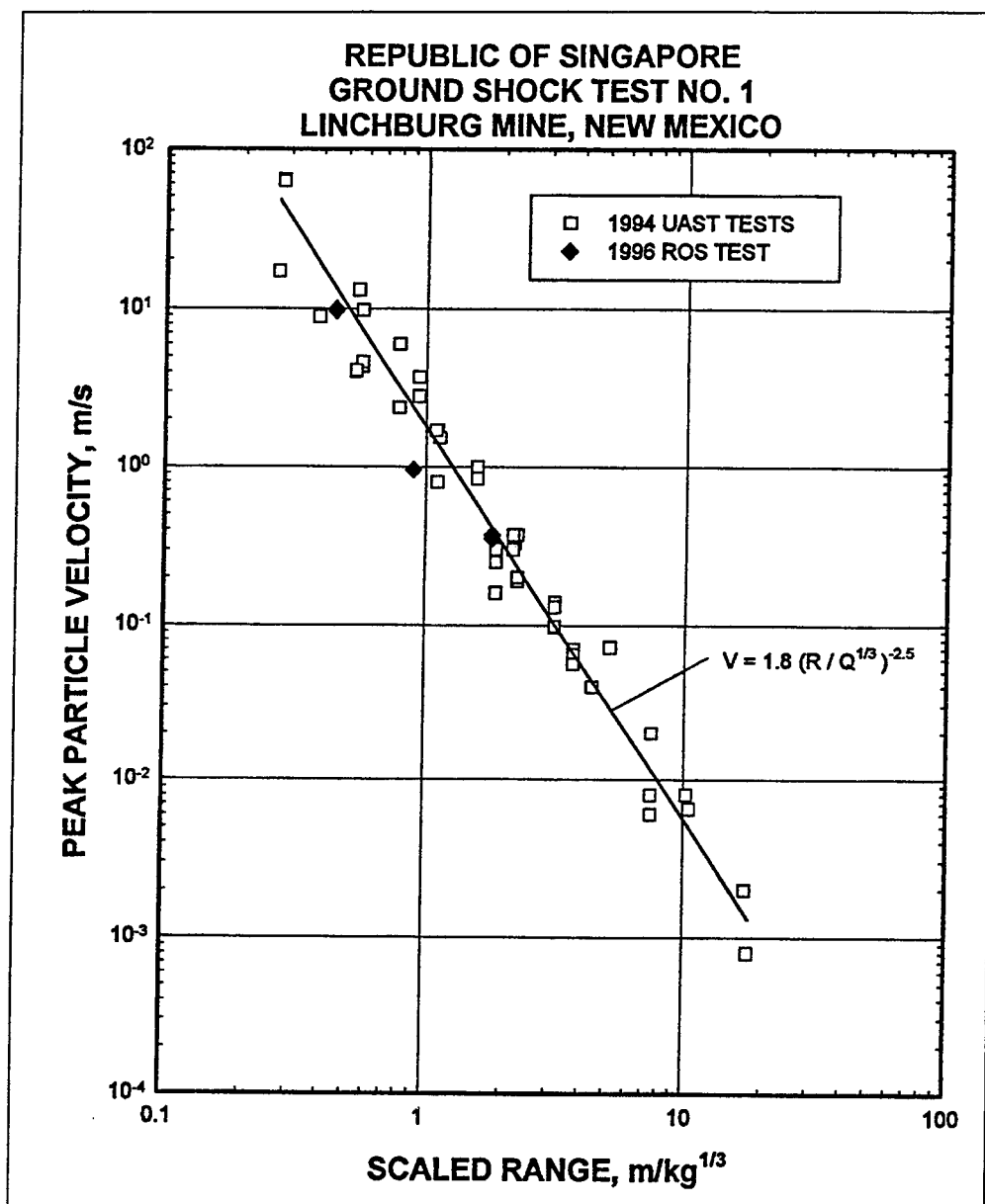


Figure 14. Peak particle velocity versus scaled range



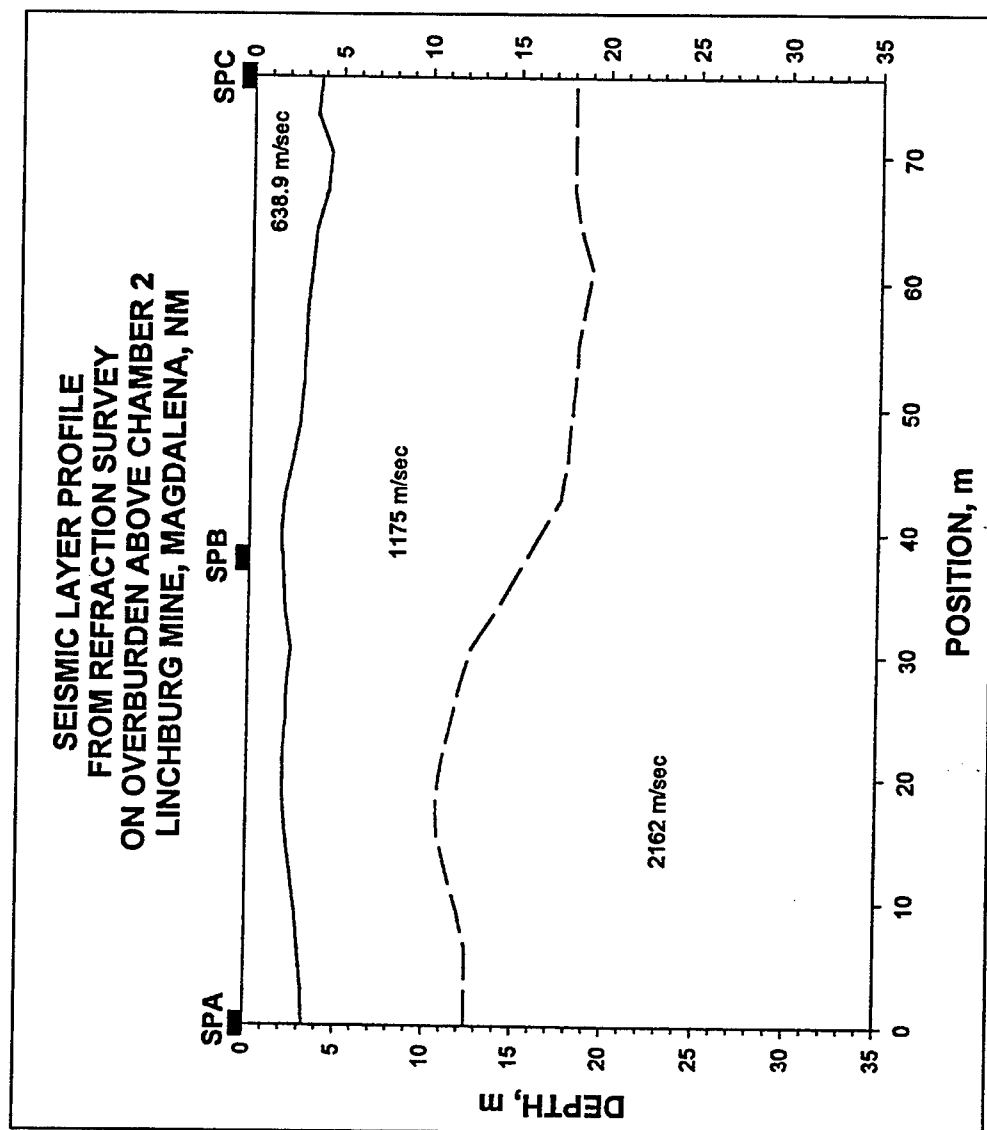


Figure 15. Seismic profile from refraction survey of overburden above test chamber at Linchburg Mine

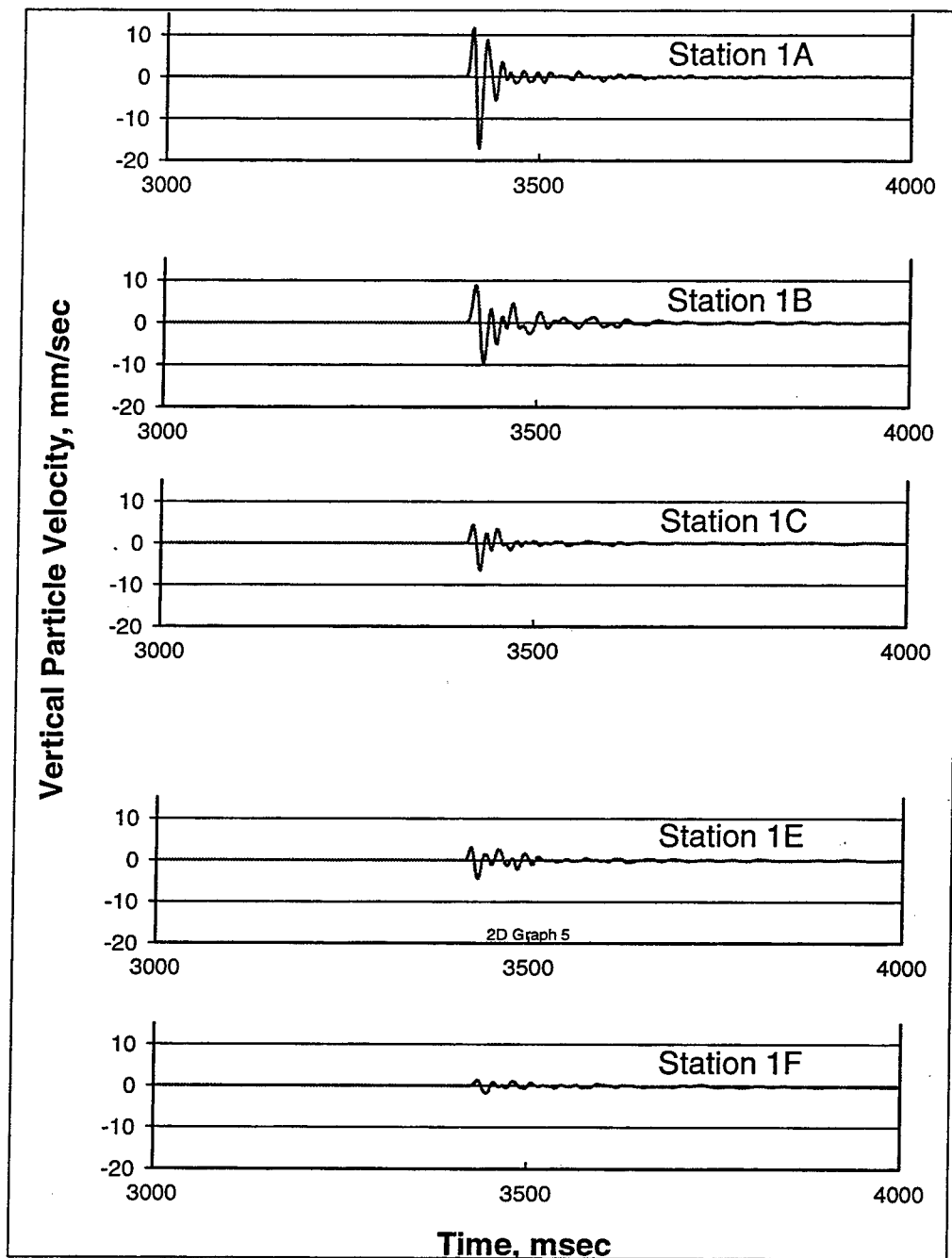


Figure 16. Vertical particle velocity-time histories from seismic transducers located on the overburden surface above Chamber 2, Singapore Ground Shock Test

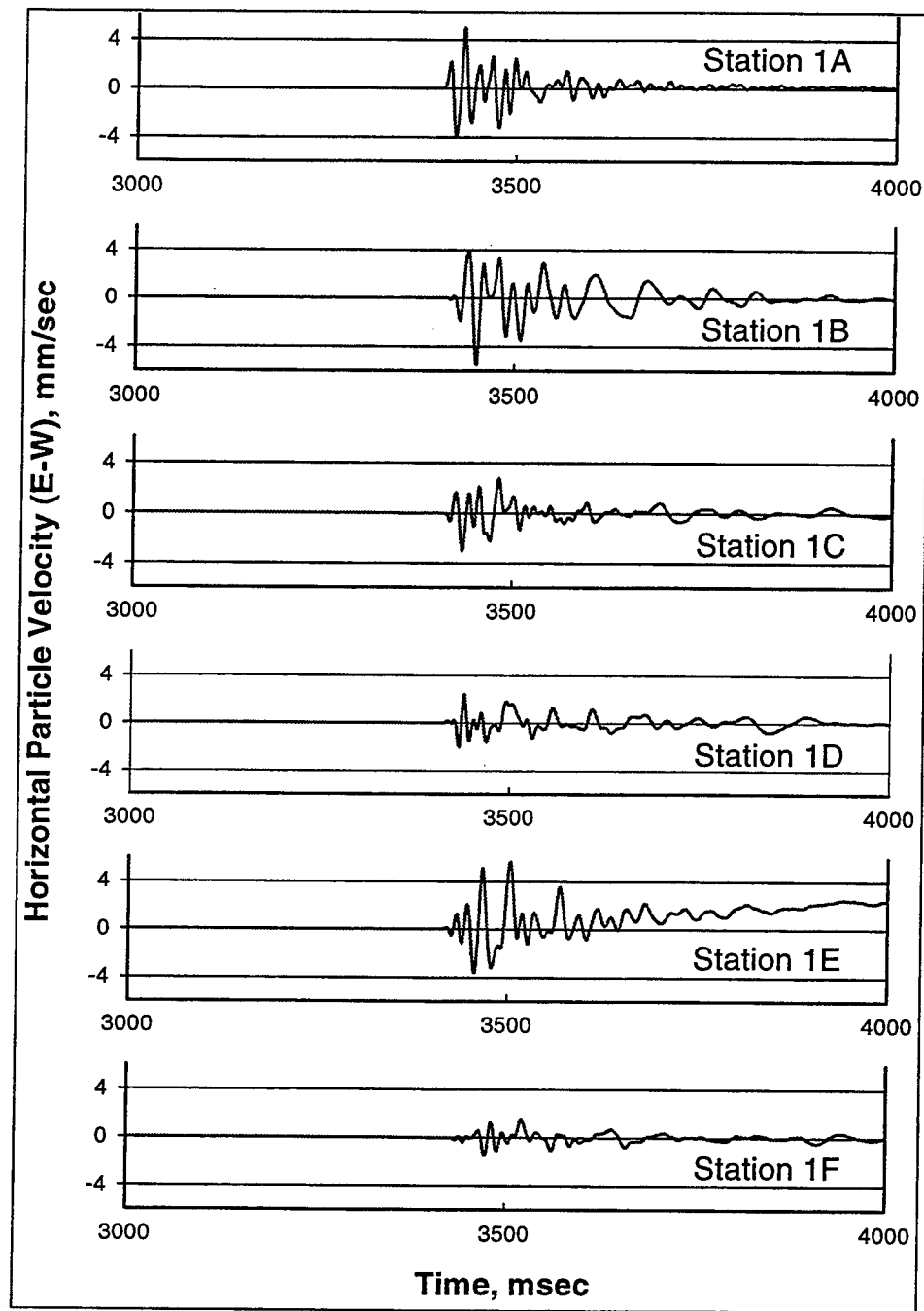


Figure 17. Horizontal (E-W) particle velocity-time histories from seismic transducers located on the overburden surface above Chamber 2, Singapore Ground Shock Test (Fig 18)

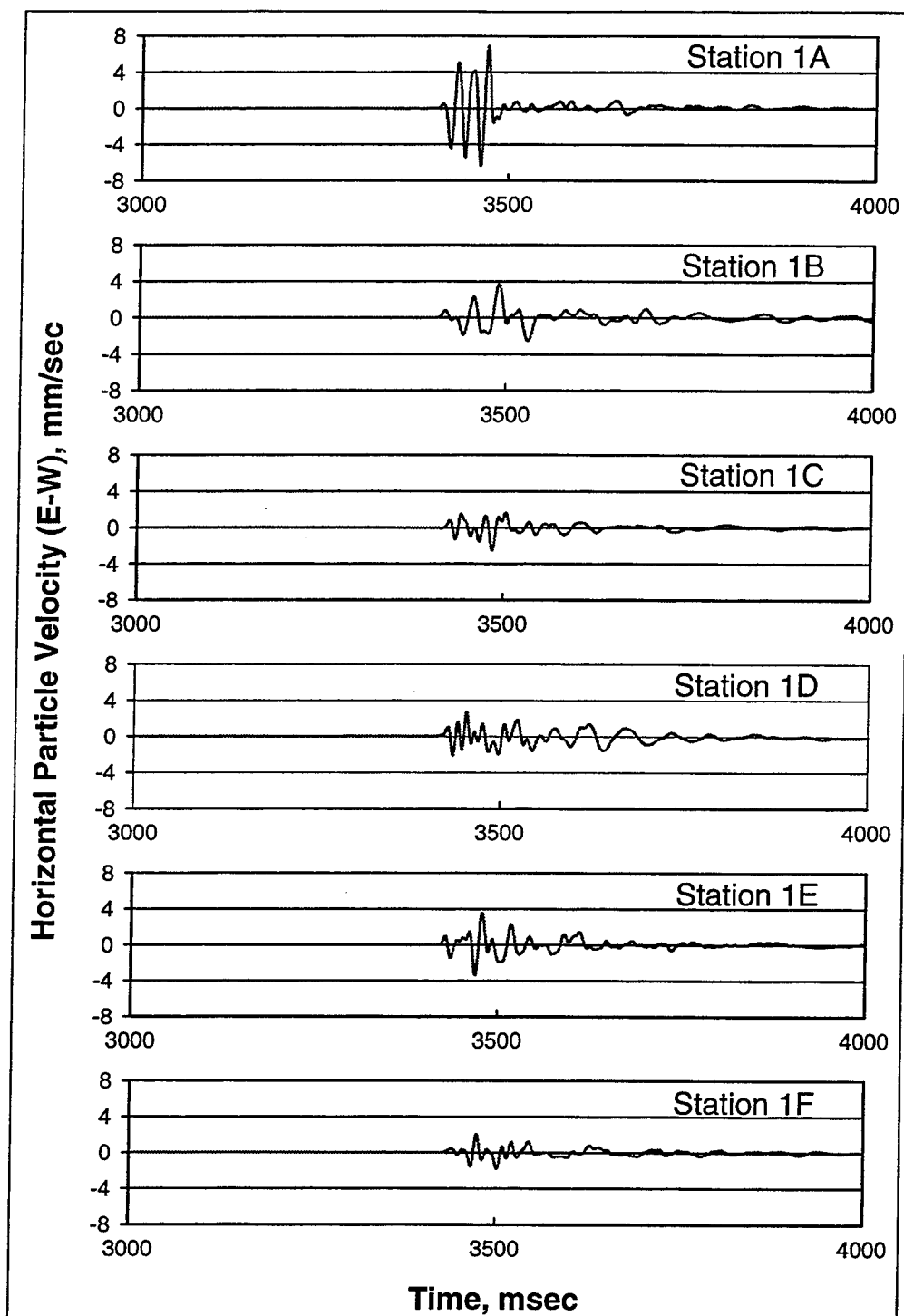


Figure 18. Horizontal (N-S) particle velocity-time histories from seismic transducers located on the overburden surface above Chamber 2, Singapore Ground Shock Test

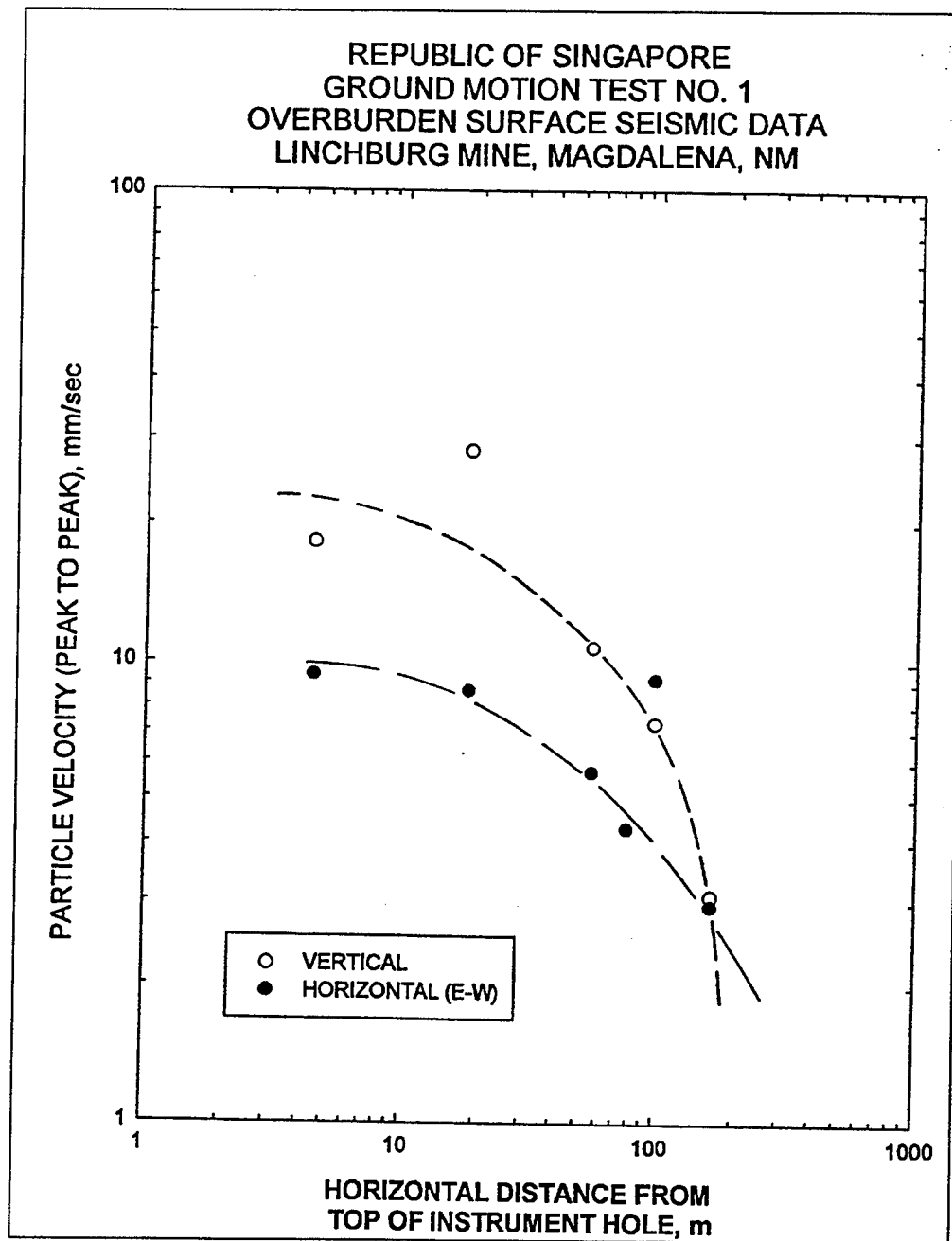


Figure 19. Peak particle velocity (peak to peak) versus horizontal distance from the top of the instrument hole, Singapore Ground Shock Test

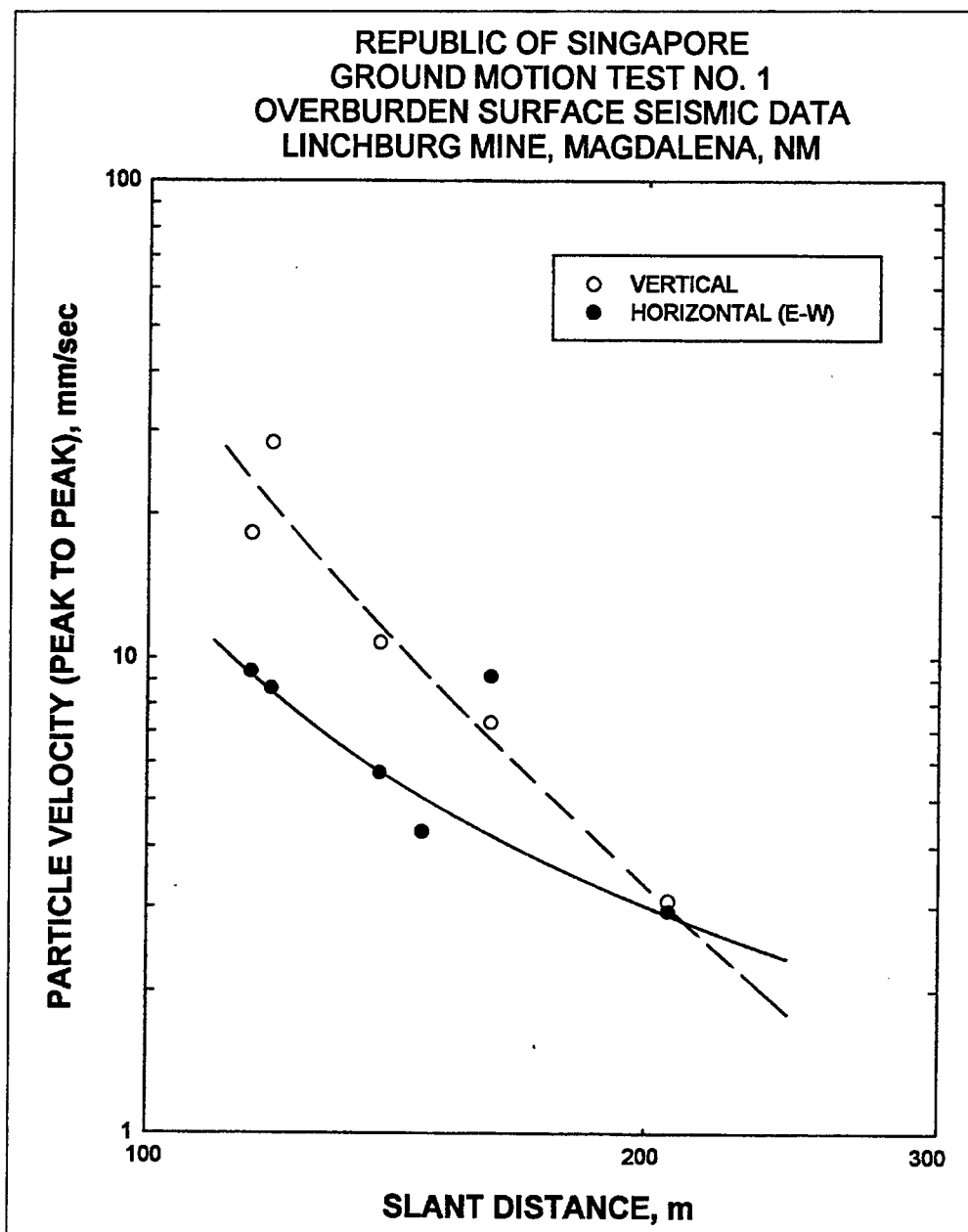


Figure 20. Peak particle velocity (peak to peak) versus slant distance from the center of the explosive charge, Chamber 2, Singapore Ground Shock Test

(radial particle velocity measurements shown in Figure 14). The surface particle velocity data are internally consistent, and attenuate with increased slant range at the same rate as the main body of data plotted in Figure 21. The surface motions are two to four times greater than the free-field velocities. This is slightly greater than the theoretical free-surface reflection factor of 2, but is in good agreement with reflection factors of 3 to 5 that are typical of surface motions recorded from underground nuclear detonations. The higher-than-theoretical reflection factors for underground tests have been attributed, in part, to the generally occurring reduction of material seismic velocity with decreasing depth below the ground surface (Figure 15).

## **Airblast Results**

### **Instrument performance**

Twenty-one of the 23 installed airblast gages produced excellent data. One gage (21 ABSO) produced a low-frequency, low-amplitude pressure record—much lower than predicted and within the noise of the digital recorder. This condition suggests that the gage cover (placed to protect the gage from damage during charge loading) was not removed prior to the detonation. The quality of the data produced by Gage 10ABSO was degraded by a defective discriminator, which affected bit resolution.

### **Arrival times**

The airblast measurements are summarized in Table 5. Pressure-time-histories, including first integrals, are presented to a duration of nine seconds in Appendix B. Initial arrival times for the airblast shock wave are plotted versus distance in Figure 22. The shock wave traveled from Chamber 2 through the chamber access drift and the North Test Drift at supersonic velocities until it reached the expansion chamber. The shock wave traveled through the Lynchburg Mine drift at an average velocity of 353.7 m/sec.

### **Peak pressures**

A typical airblast pressure-time history is shown in Figure 23. The waveform typically consists of two parts; an initial shock wave and a long-duration gas pressure. The peak overpressures (of both components) are plotted versus distance from the rear wall of the detonation chamber (Chamber 2) in Figure 24. The comparison shows that the shock pressure clearly dominated as the blast wave traveled from the test chamber into the North Test Drift (Gages 16 and 11). The peak pressures calculated for this test, using the BLASTX computer code (Version 3.5.3), are included in Figure 24 for comparison.

After the blast wave entered the expansion chamber, reflections and rarefactions of the shock reduced the peak shock pressures to values near those of the gas pressures (Gages 1 OB and 10C). As the blast wave traveled down the

**Table 5.**  
**Airblast Data Summary**

Gage No.	Gage Location	Distance from Rear Wall of Chamber 2 (m)	Arrival Time (msec)	Peak Pressure		Peak Impulse (kPa-sec)
				Shock (kPa)	Gas (kPa)	
1	Linchburg Mine	323.7	746.6	18.90	4.29	23.83
3	Linchburg Mine	246.4	529.4	26.32	19.46	105.5
4	Exp. Chamber	182.6	347.7	39.46	34.38	174.1
10A	Exp. Chamber	89.98	98.66	111.9	82.81	338.2
10B	Exp. Chamber	75.98	71.97	142.2	96.39	393.3
10D	Exp. Chamber	89.98	97.64	133.2	102.6	387.9
11	N. Test Drift	50.67	37.56	598.5	124.6	523.4
16	N. Test Drift	39.51	24.16	835.6	161.8	430.4
18	Ch. Access	25.19	9.53	2911.00	437.6	248.1
19	Ch. Access	20.82	6.08	2705.00	1534.0	--
20	Debris Tray	14.73	4.96	--	32.12	--
21	Debris Tray	16.13	5.81	15072.00	1147.0	1,049.0
59	Outside Portal	334.9	807.3	3.77	1.05	0.083
60	Outside Portal	339.9	793.3	2.36	2.06	0.035
63	Outside Portal	359.9	866.6	0.68	0.089	0.013



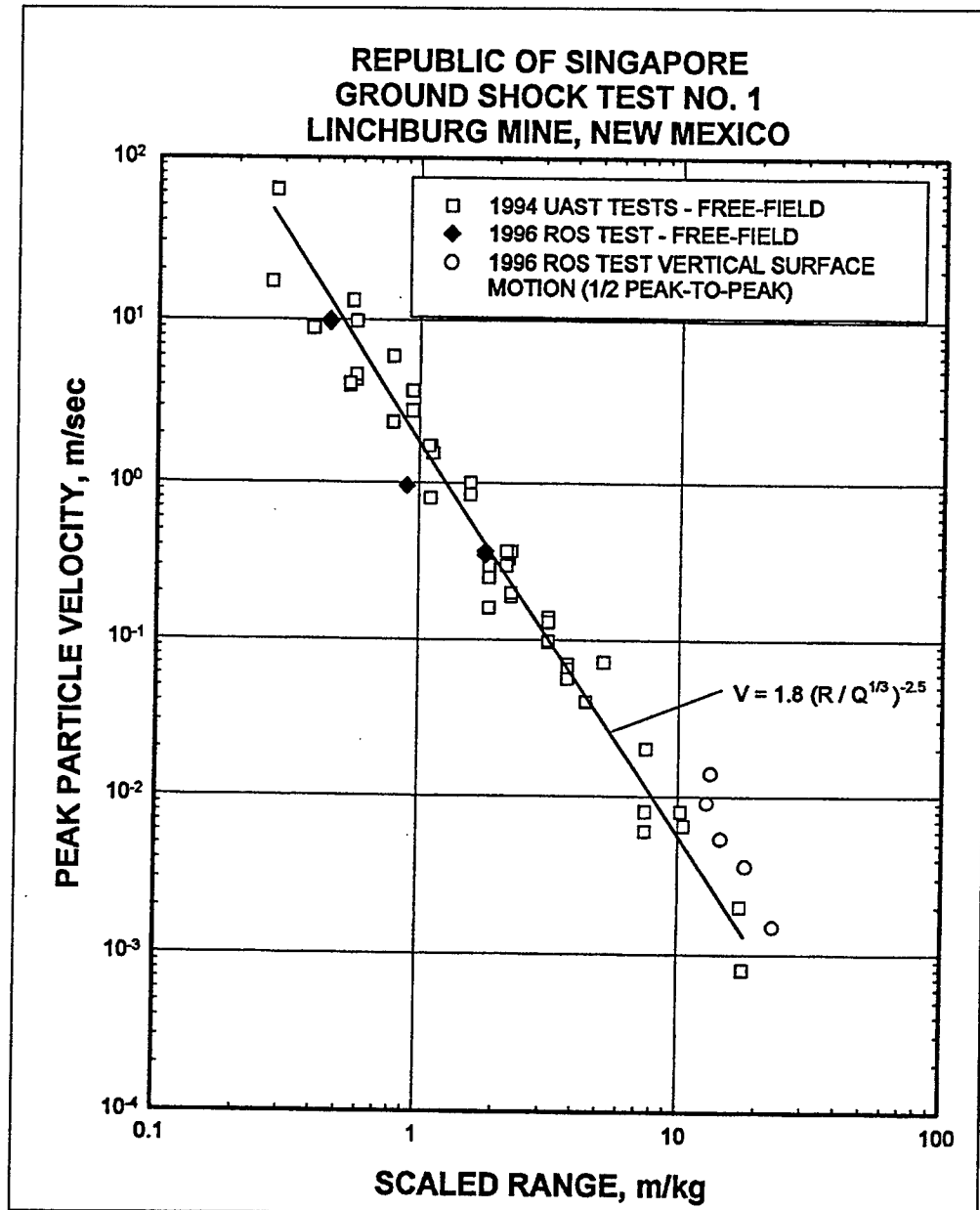


Figure 21. Comparison of vertical surface motion particle velocities (open circle symbols) with radial free-field velocities, all as a function of scaled range from the charge center, Singapore Ground Shock Test

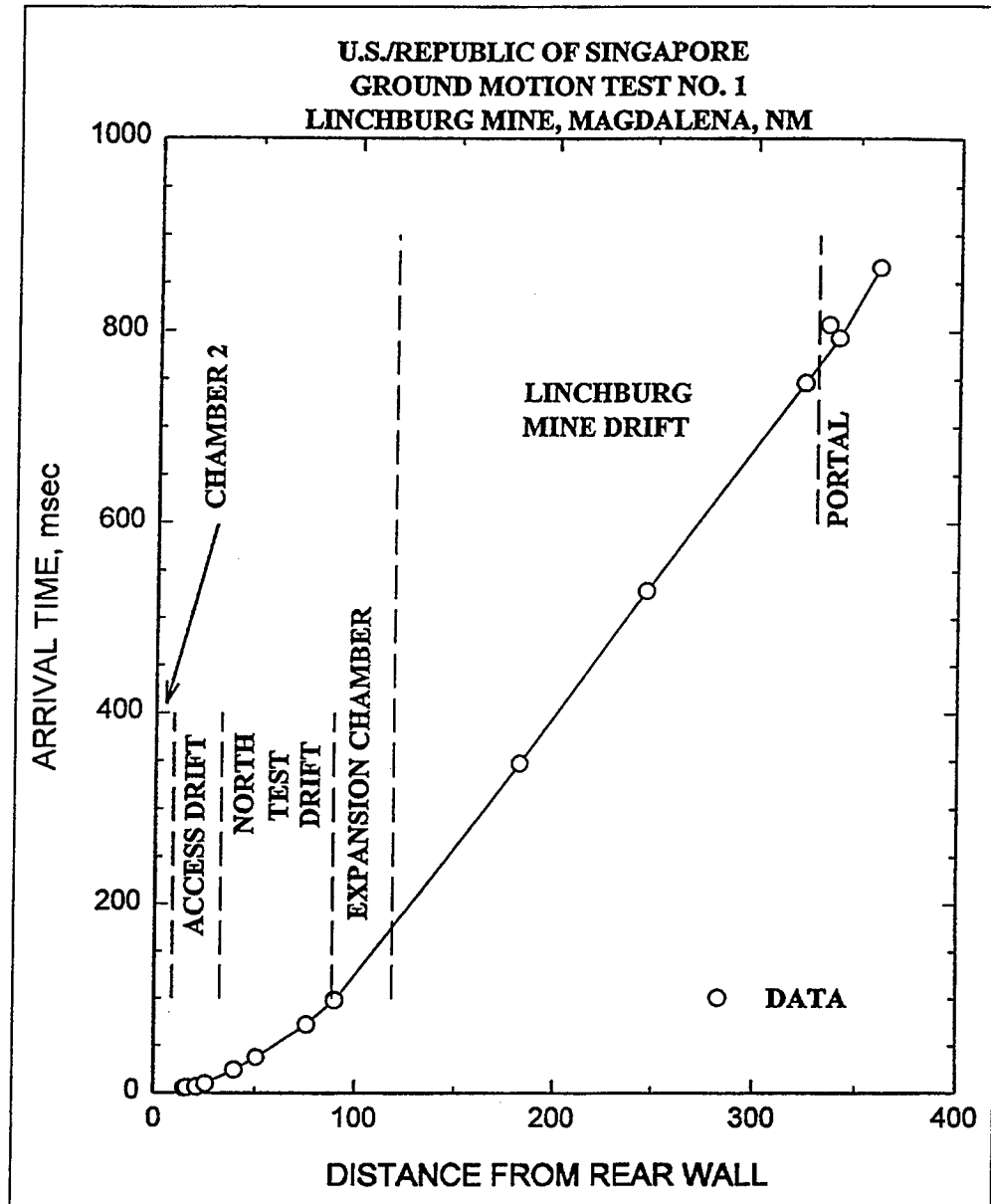


Figure 22. Airblast shock front arrival time versus distance from the rear wall of Chamber 2, Singapore Ground Shock Test

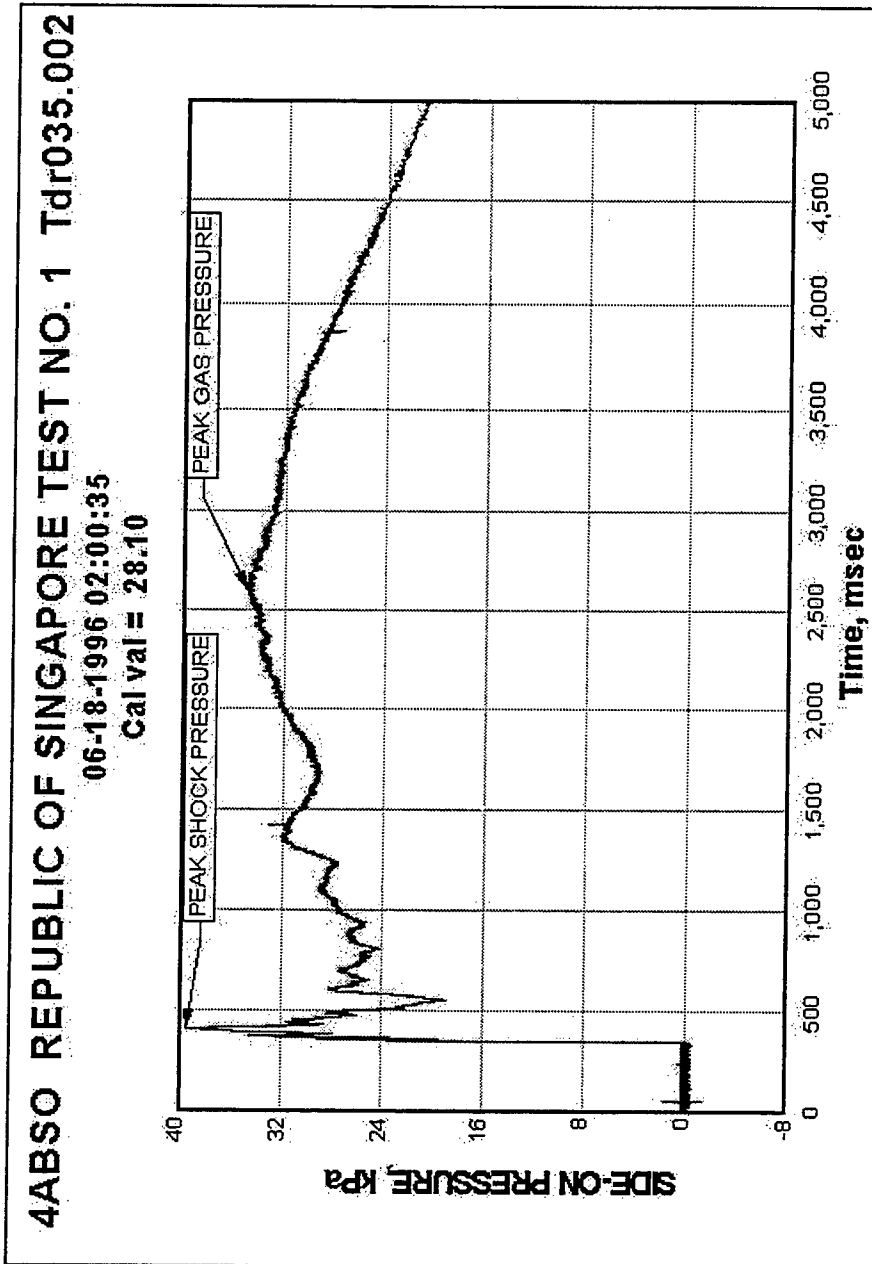


Figure 23. Typical underground airblast pressure-time history with shock and gas components, Singapore Ground Shock Tests

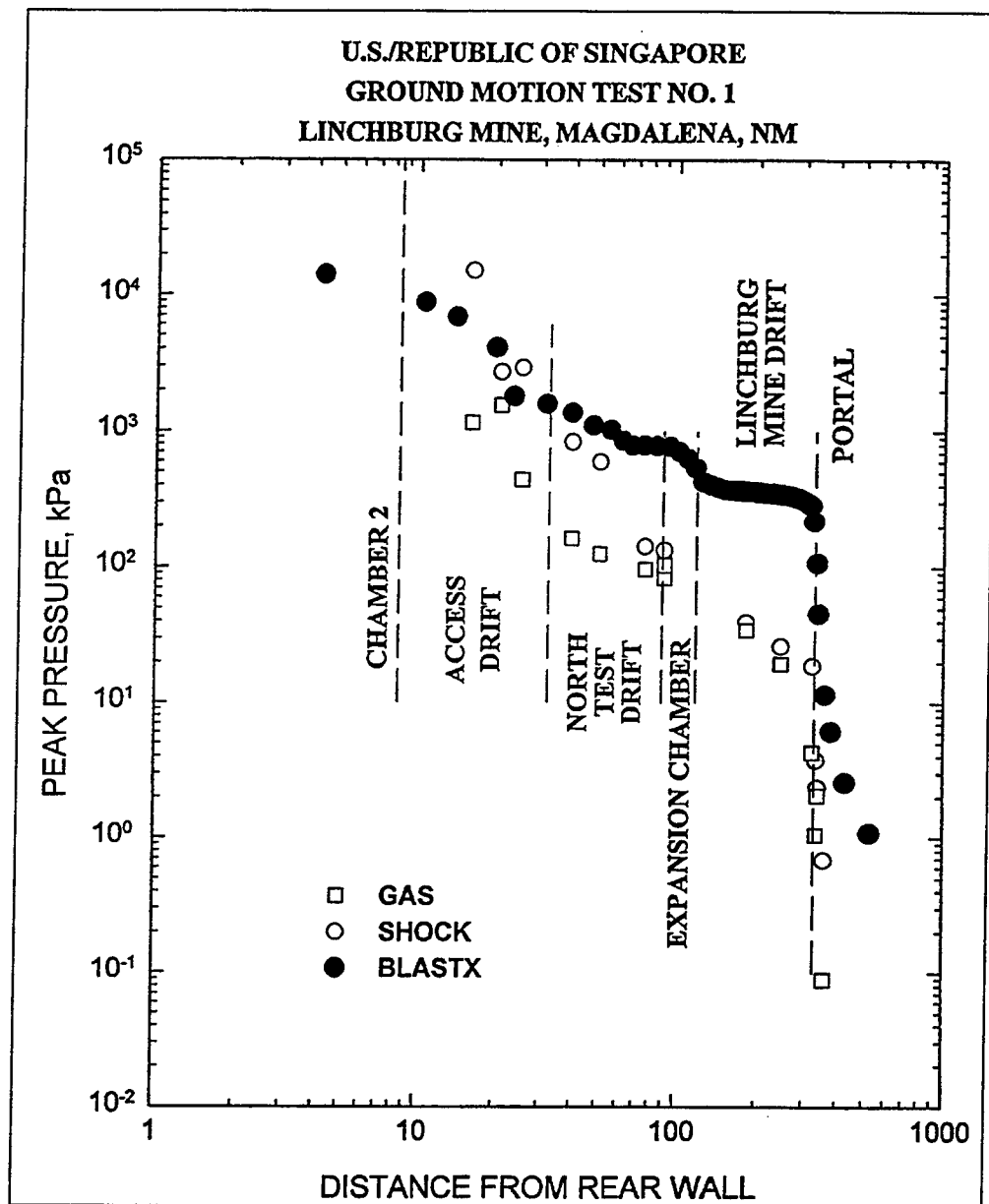


Figure 24. Peak overpressure versus distance from the rear wall of Chamber 2, Singapore Ground Shock Test

Linchburg Mine, the gas pressures dropped steadily with the additional engulfed volume. The shock front, however, reformed and moved toward the portal as more-or-less one-dimensional wave propagation, with little loss of energy (Gage 1). The shock front emerged from the tunnel portal and traveled at sonic velocity toward the external gages, where its brief passage is clearly seen as an initial, short-duration pressure spike (Gages 59 and 60). Once the gas pressure escaped the confinement of the tunnel, however, the gas flow slowed down and quickly dissipated.

### **Peak impulse**

Airblast impulse-time histories were obtained by integration of the recorded overpressure-time histories. Peak impulse values are plotted versus distance in Figure 25. An attempt has been made to separate the gas and shock-produced impulse, where possible.

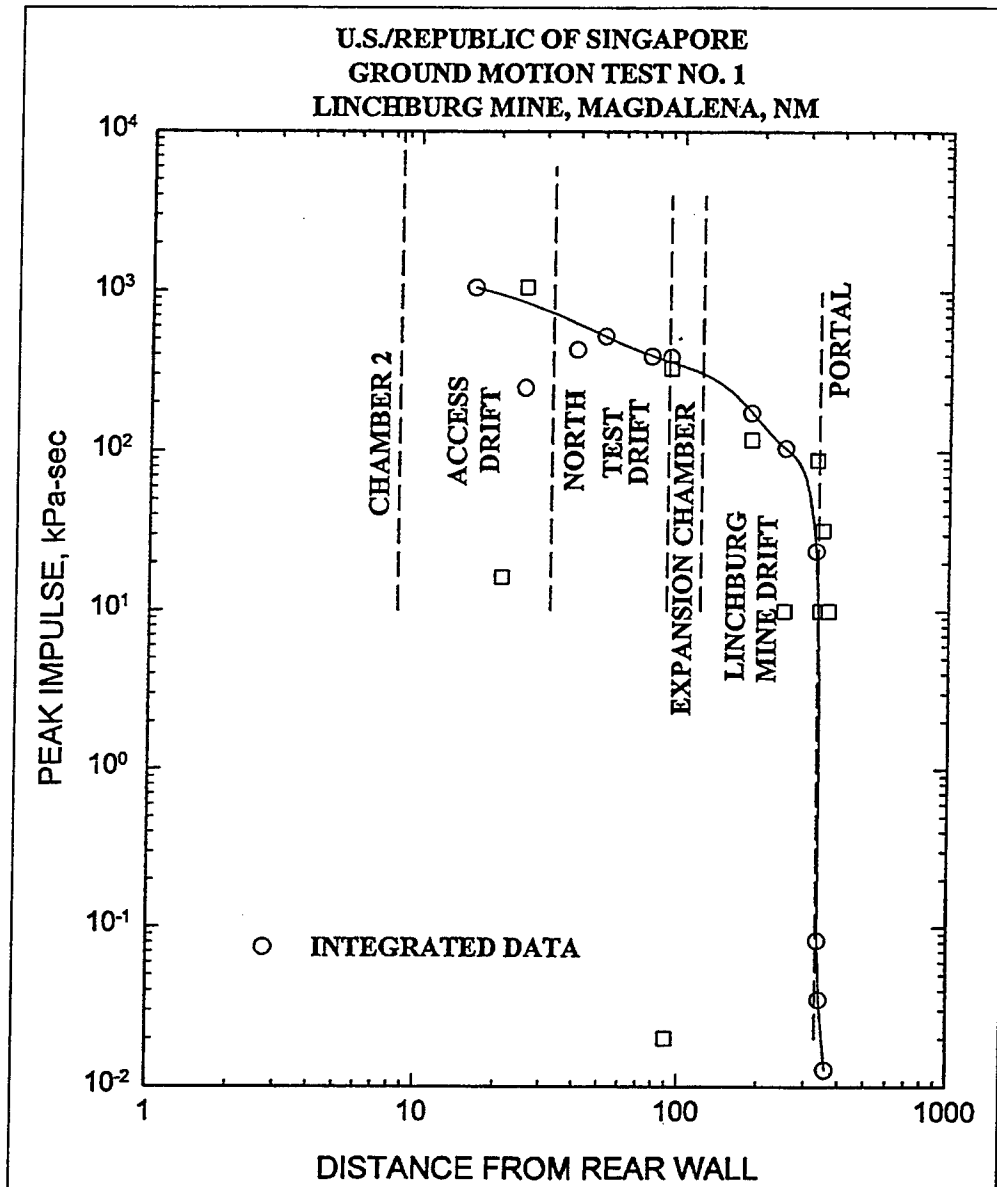


Figure 25. Peak overpressure impulse versus distance from rear wall of Chamber 2, Singapore Ground Shock Test

## 4 Conclusions and Recommendations

---

### Conclusions

The measured airblast pressure data (underground and free-field) were consistent and indicated a complete detonation of the explosive charge. The ground motion data from integrated acceleration-time histories in the vertical bore hole are in good agreement with data from previous UAST detonations at this site.

Comparison of these data and the surface motion values show that both data sets attenuate at the rate  $R_s^{-2.5}$ . The surface motion reflection factor was slightly greater than the theoretical free-surface value, but was in good agreement with reflection factors of 3 to 5 that have been observed on underground nuclear tests.

### Recommendations

The aim of underground ammunition storage research to date has been reduction of external airblast and debris hazards from accidental detonations. The ground shock hazard distances were secondary until these hazards were significantly reduced. Underground ammunition storage facilities designed for use in Singapore must also consider reduction in ground shock hazards. Therefore, a comprehensive ground motion research program is needed to evaluate the ground shock hazards at the proposed site in Singapore. The study should evaluate the effects of decoupled detonations and shock isolation techniques on ground shock hazards.

# References

---

- L. K. Davis. (1995). "Explosive Hazard Analysis For Design of Underground Magazines," Research Proposal submitted to the Republic of Singapore, Ministry of Defence, by U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- J. Wesley Martin. (1994). "Material Characterization of Samples from the Linchburg Mine," TeraTek, Inc., Salt Lake City, UT.



# **Appendix A**

## **1996 Singapore**

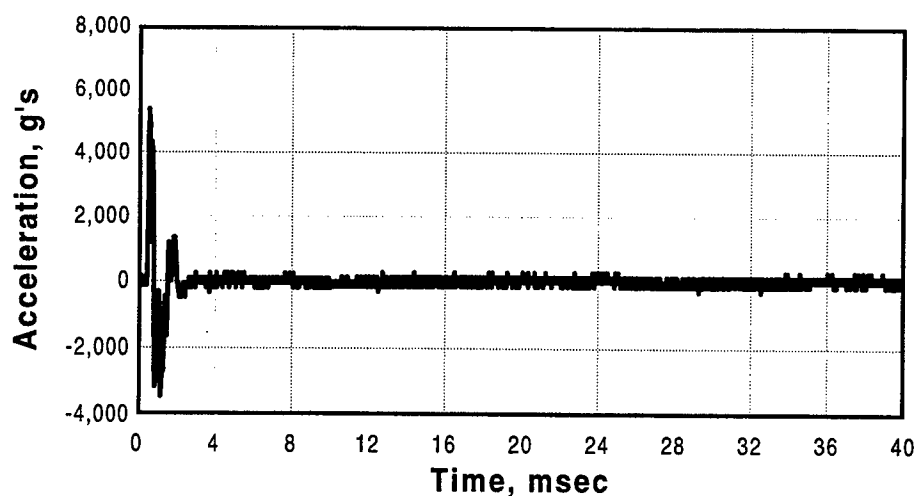
### **Ground Shock Time-Histories**

---

**Acceleration-, Particle Velocity- and Displacement-Time -  
Histories from the Detonation of 696.6 kg of Composition B  
Explosive**

## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR001, Gage 204A, 4 m  
Linchburg Mine, Magdalena, NM



## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR001, Gage 204A, 4 m  
Linchburg Mine, Magdalena, NM

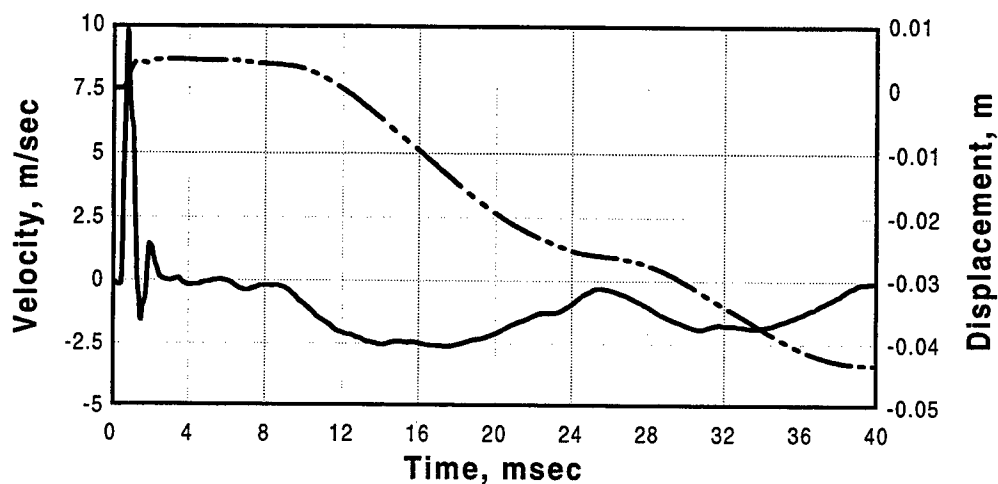
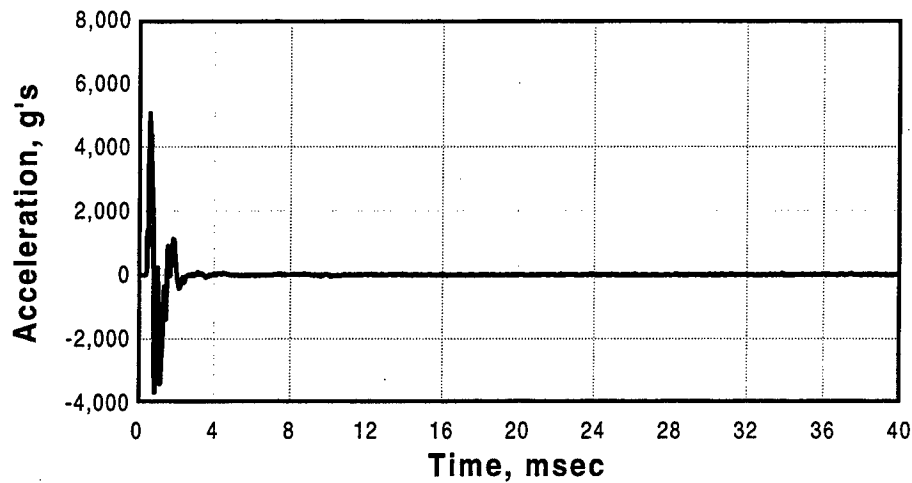


Figure A1. Vertical ground motion: acceleration-, velocity-, and displacement-time histories at Station 204A, 4 m from the center of Chamber 2, Singapore Ground Shock Test.

## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR002, Gage 204B, 4 m  
Linchburg Mine, Magdalena, NM



## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR002, Gage 204B, 4 m  
Linchburg Mine, Magdalena, NM

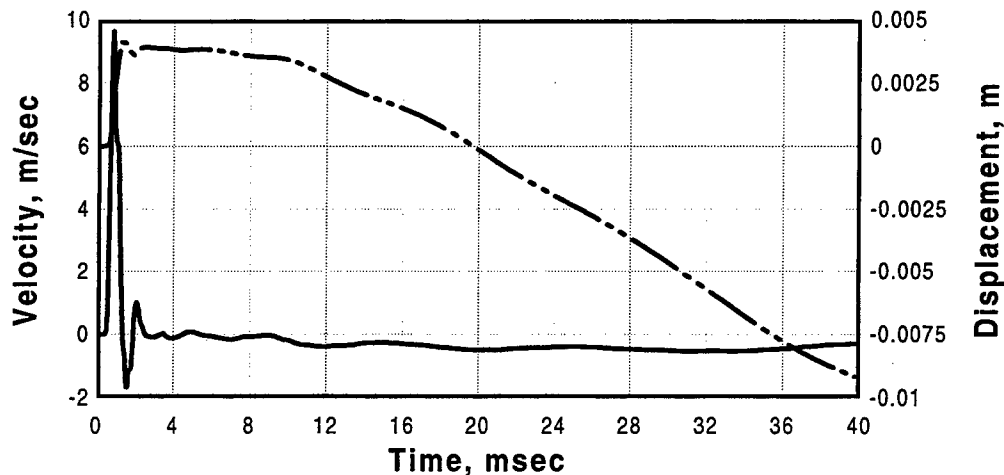
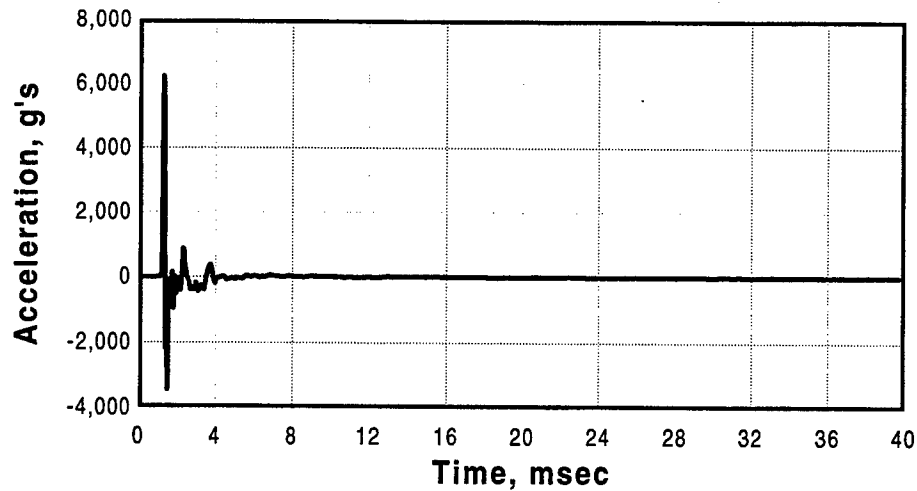


Figure A2. Vertical ground motion: acceleration-, velocity-, and displacement-time histories at Station 204B, 4 m from the center of Chamber 2, Singapore Ground Shock Test.

## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR003, Gage 208A, 8 m  
Linchburg Mine, Magdalena, NM



## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR003, Gage 208A, 8 m  
Linchburg Mine, Magdalena, NM

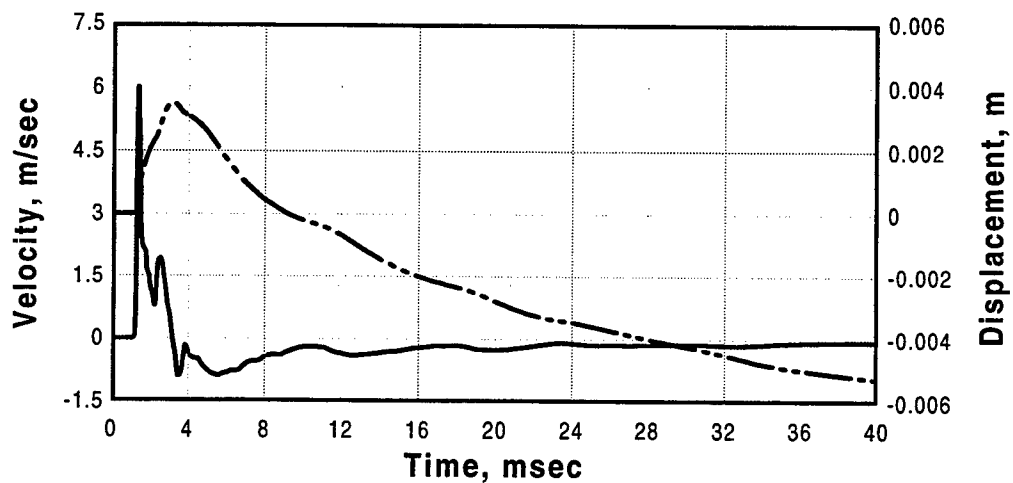
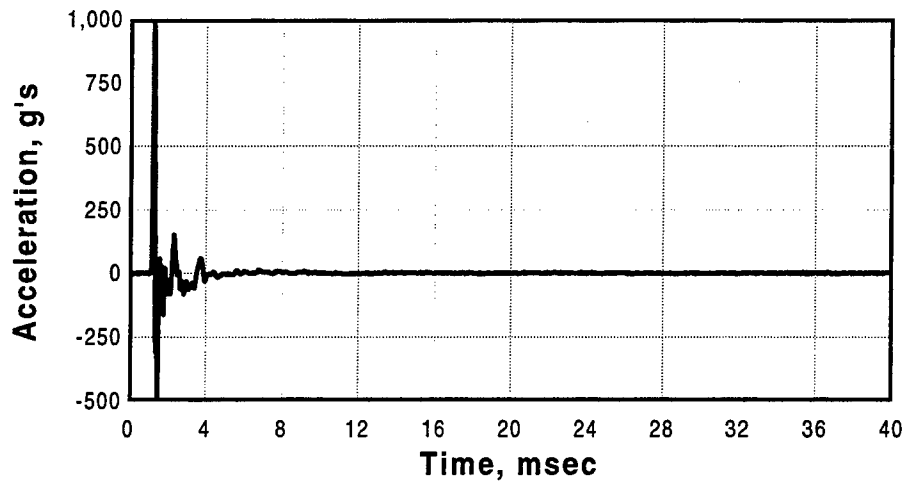


Figure A3. Vertical ground motion: acceleration-, velocity-, and displacement-time histories at Station 208A, 8 m from the center of Chamber 2, Singapore Ground Shock Test.

## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR004, Gage 208B, 8 m  
Linchburg Mine, Magdalena, NM



## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR004, Gage 208B, 8 m  
Linchburg Mine, Magdalena, NM

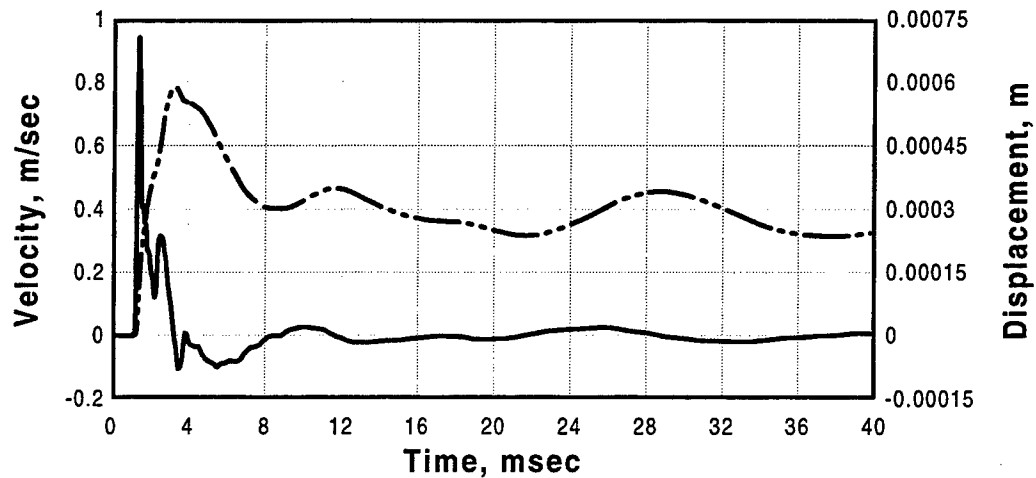
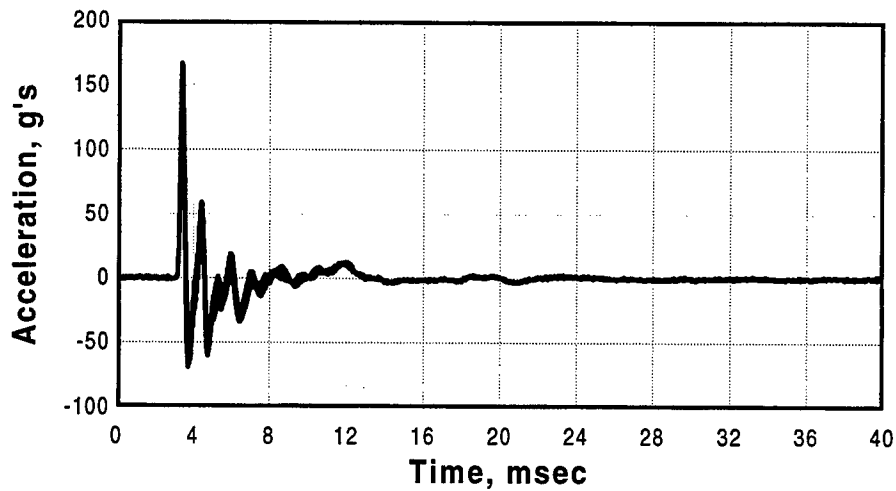


Figure A4. Vertical ground motion: acceleration-, velocity-, and displacement-time histories at Station 208B, 8 m from the center of Chamber 2, Singapore Ground Shock Test.

## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR005, Gage 216A, 16 m  
Linchburg Mine, Magdalena, NM



## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR005, Gage 216A, 16 m  
Linchburg Mine, Magdalena, NM

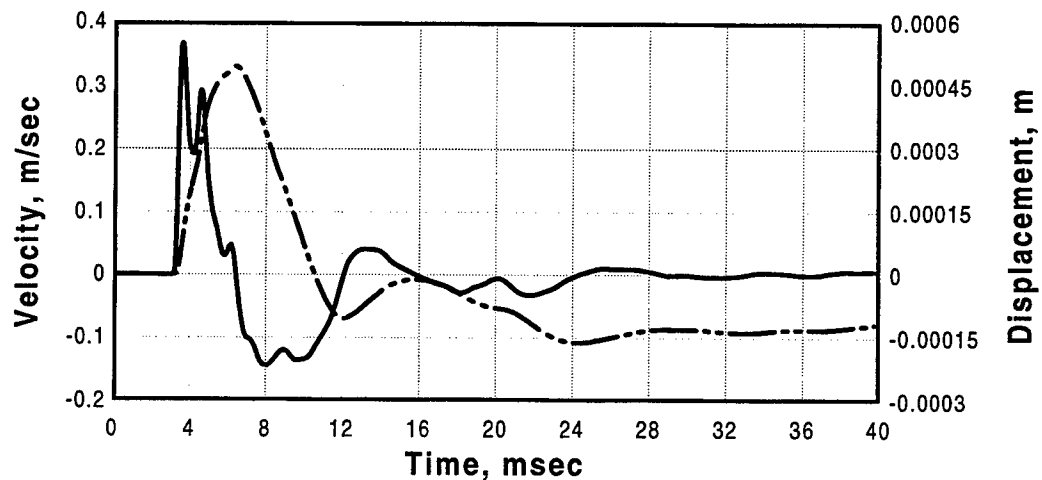
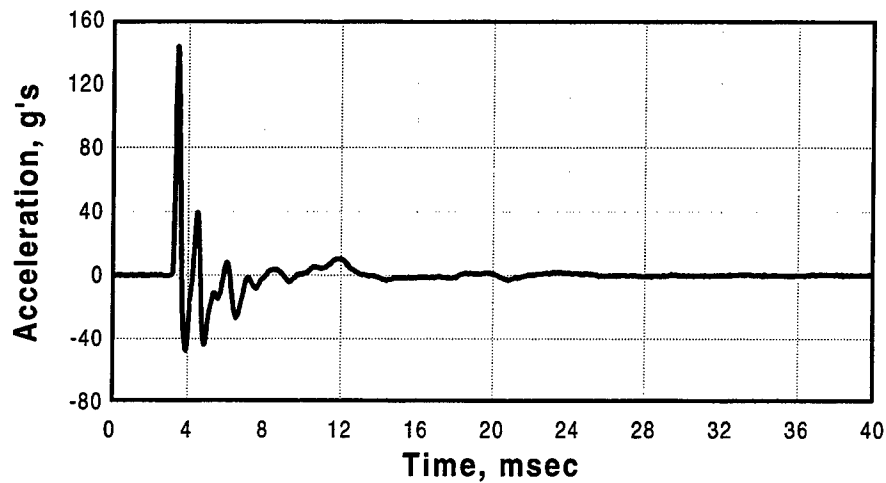


Figure A5. Vertical ground motion: acceleration-, velocity-, and displacement-time histories at Station 216A, 16 m from the center of Chamber 2, Singapore Ground Shock Test.

## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR006, Gage 216B, 16 m  
Linchburg Mine, Magdalena, NM



## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR006, Gage 216B, 16 m  
Linchburg Mine, Magdalena, NM

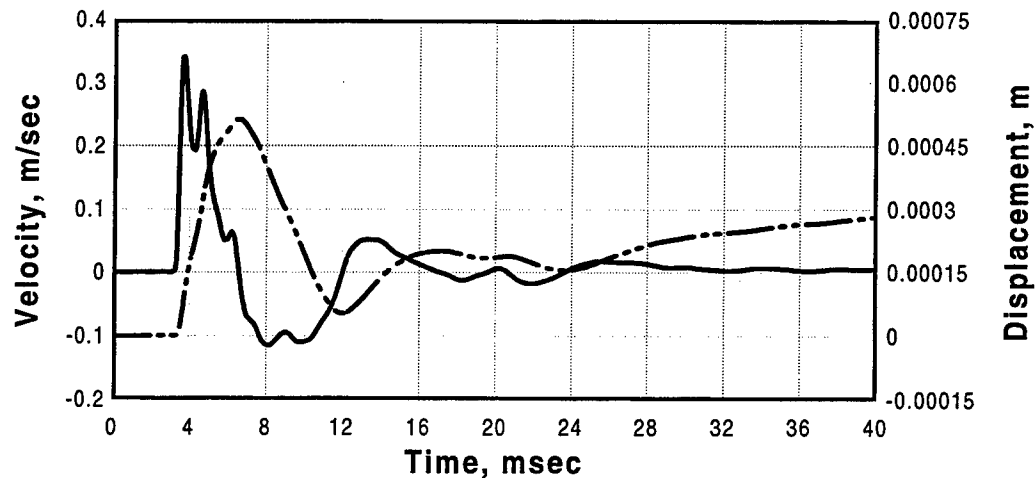
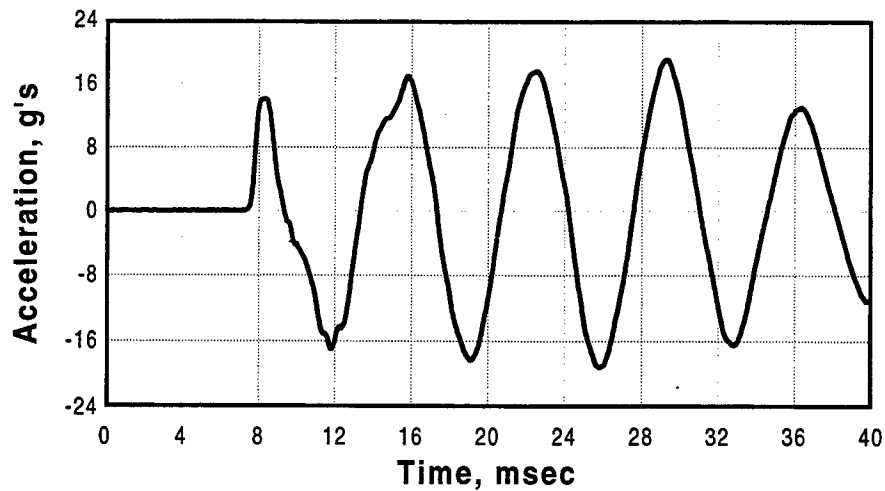


Figure A6. Vertical ground motion: acceleration-, velocity-, and displacement-time histories at Station 216B, 16 m from the center of Chamber 2, Singapore Ground Shock Test.

## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR007, Gage 232A, 32 m  
Linchburg Mine, Magdalena, NM



## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR007, Gage 232A, 32 m  
Linchburg Mine, Magdalena, NM

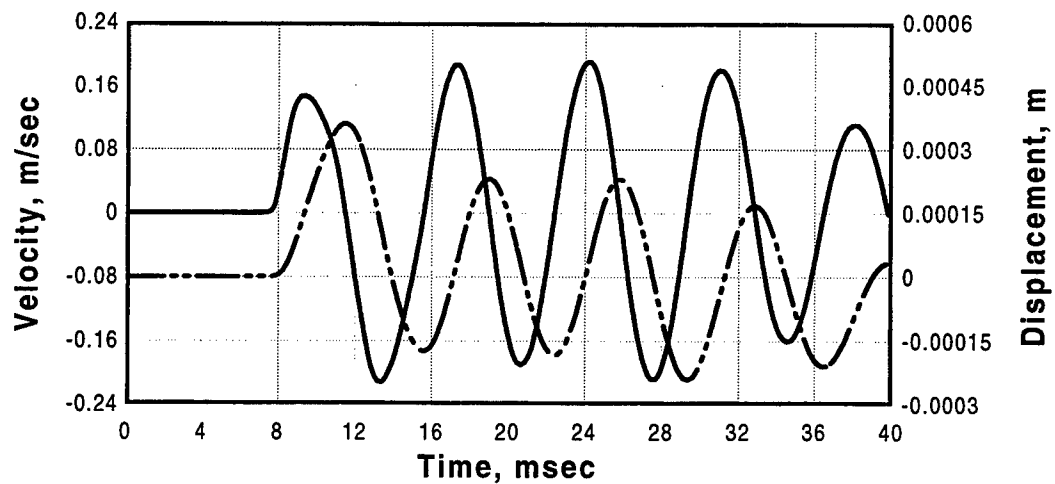
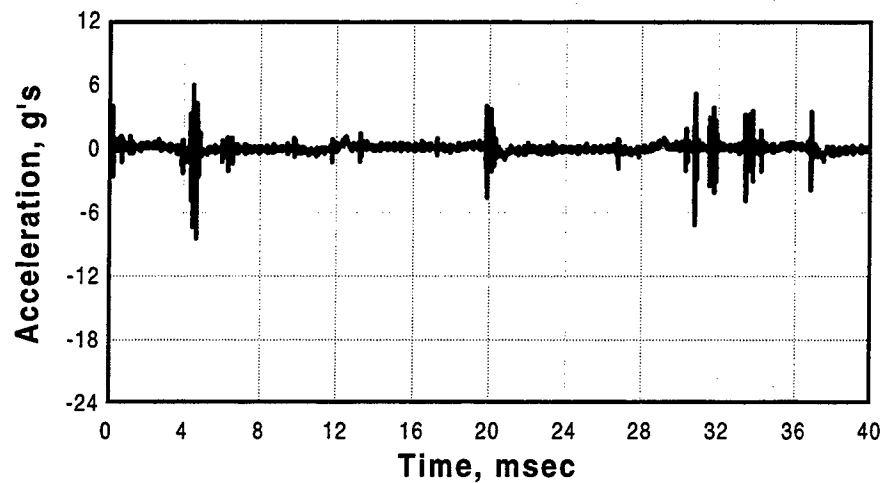


Figure A7. Vertical ground motion: acceleration-, velocity-, and displacement-time histories at Station 232A, 32 m from the center of Chamber 2, Singapore Ground Shock Test.



## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR008, Gage 232B, 32 m  
Linchburg Mine, Magdalena, NM



## REPUBLIC OF SINGAPORE GROUND SHOCK TEST

TDR008, Gage 232B, 32 m  
Linchburg Mine, Magdalena, NM

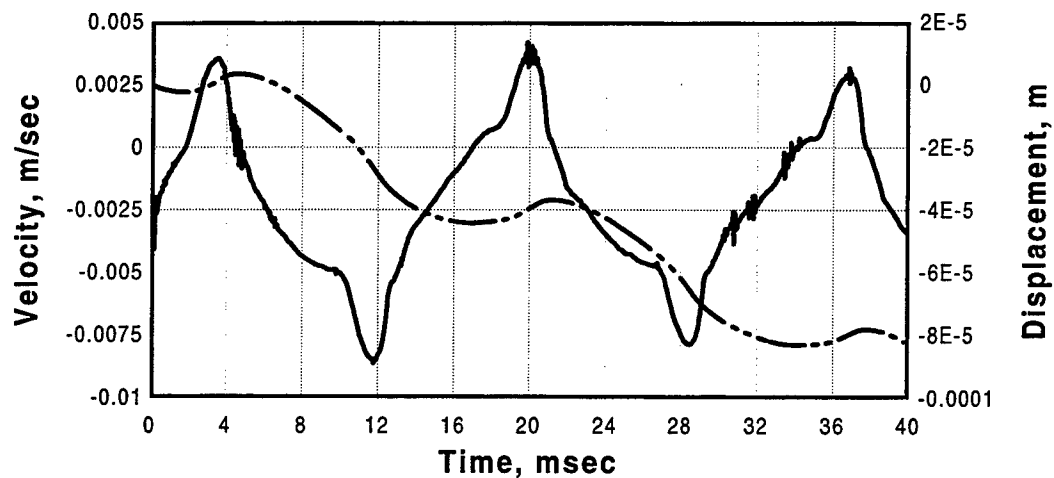


Figure A8. Vertical ground motion: acceleration-, velocity-, and displacement-time histories at Station 232B, 32 m from the center of Chamber 2, Singapore Ground Shock Test.

# **Appendix B**

## **Singapore Ground Shock Test: Airblast Pressure Time-Histories**

---

**Pressure- and Impulse-Time-Histories from the Detonation  
of 696.6 kg of Composition B Explosive**

# 20ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=2069.451, CBS=1.0181

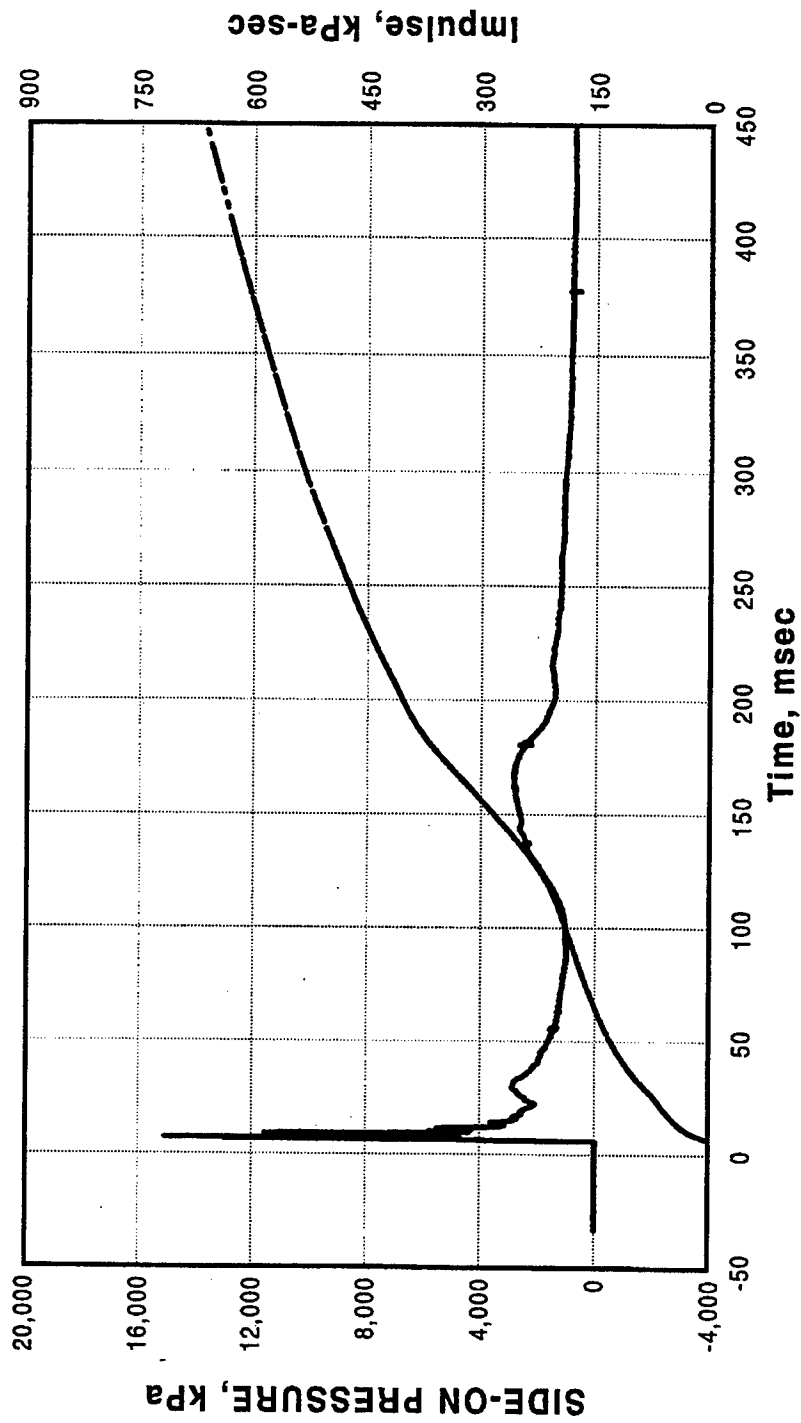


Figure B1. Gage 20ABSO airblast overpressure- and impulse-time-histories (450 msec record), Singapore Ground Shock Test.

# 20ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=2069.451, CBS=1.0181

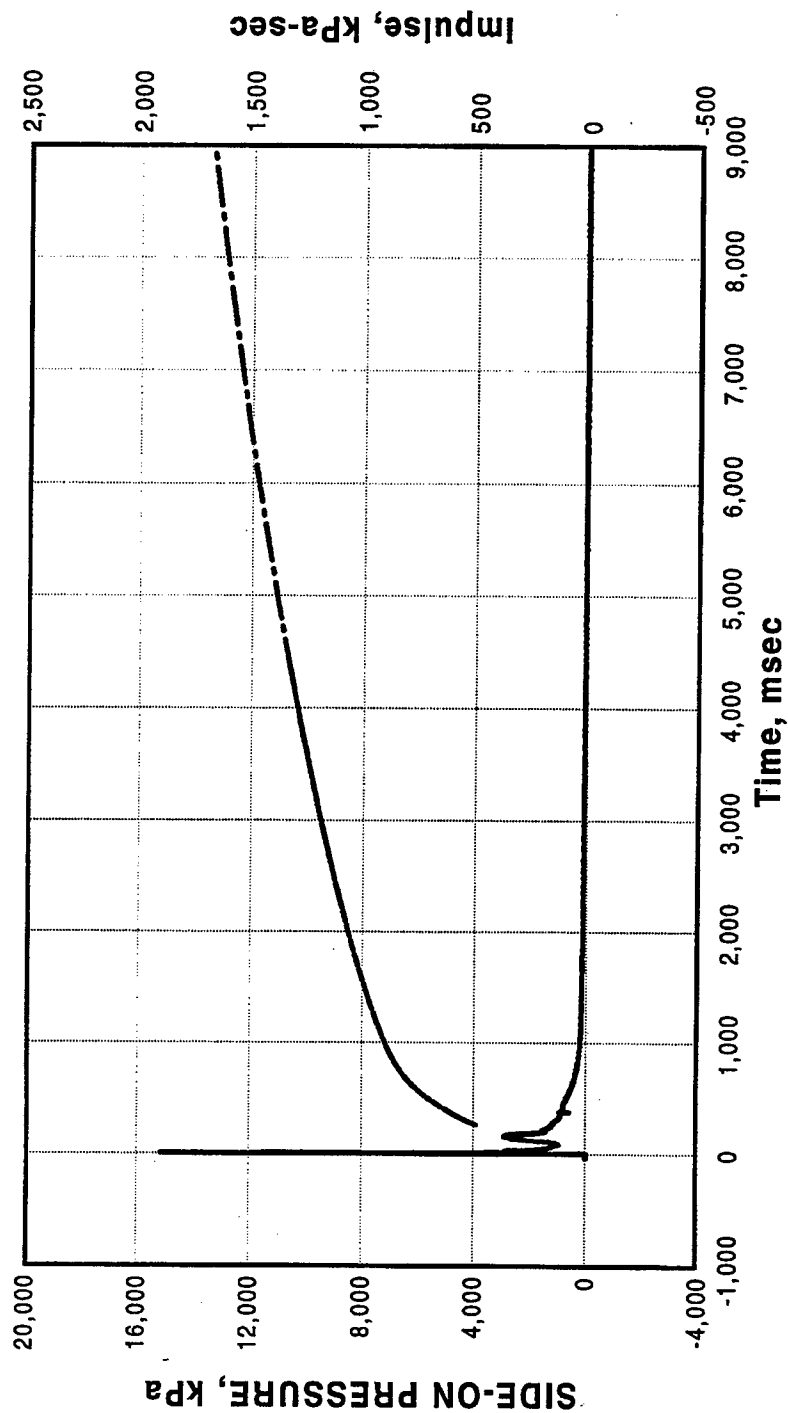


Figure B2. Gage 20ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.

# 21ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=1770.29, CBS=-0.509338

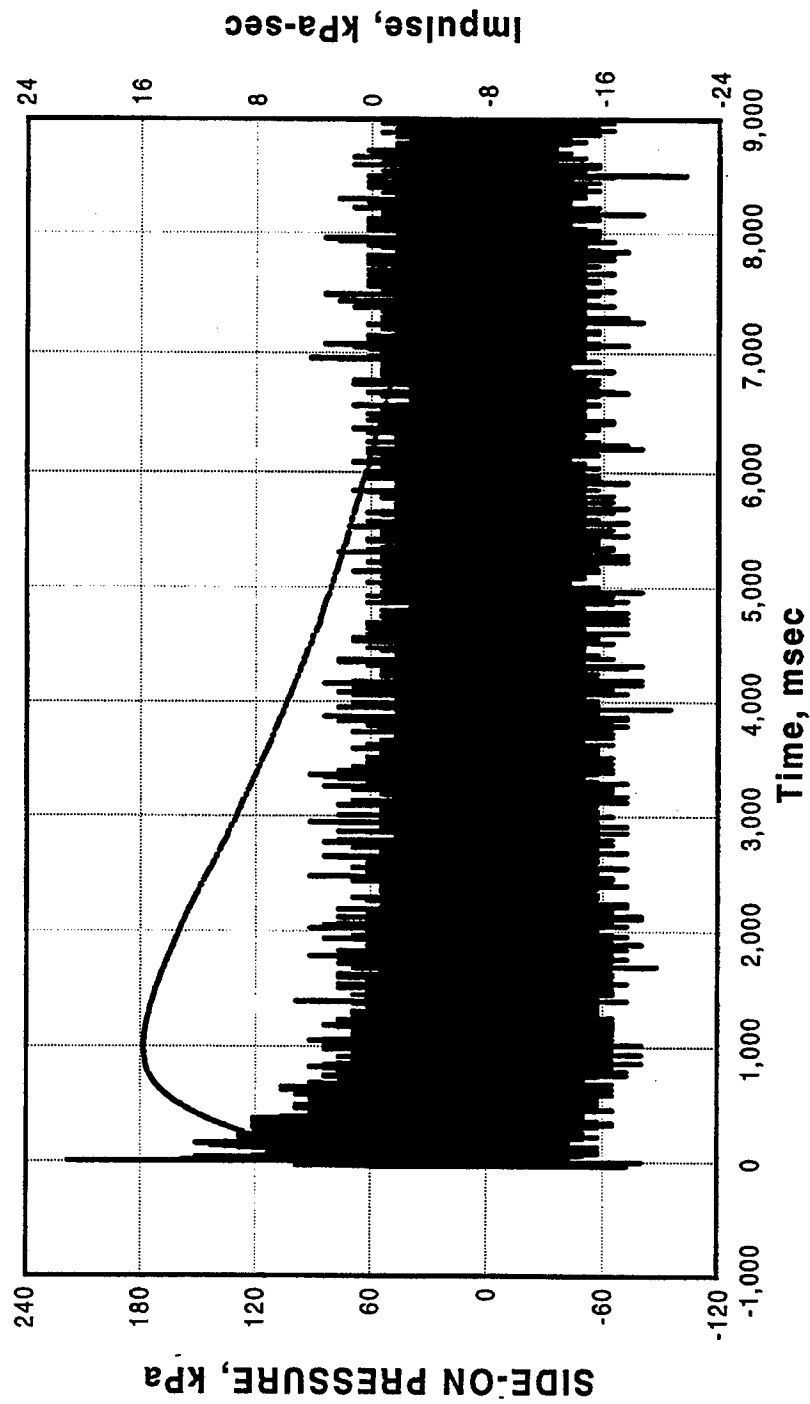


Figure B3. Gage 21ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.

# 19ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=1132.254, CBS=1.19543

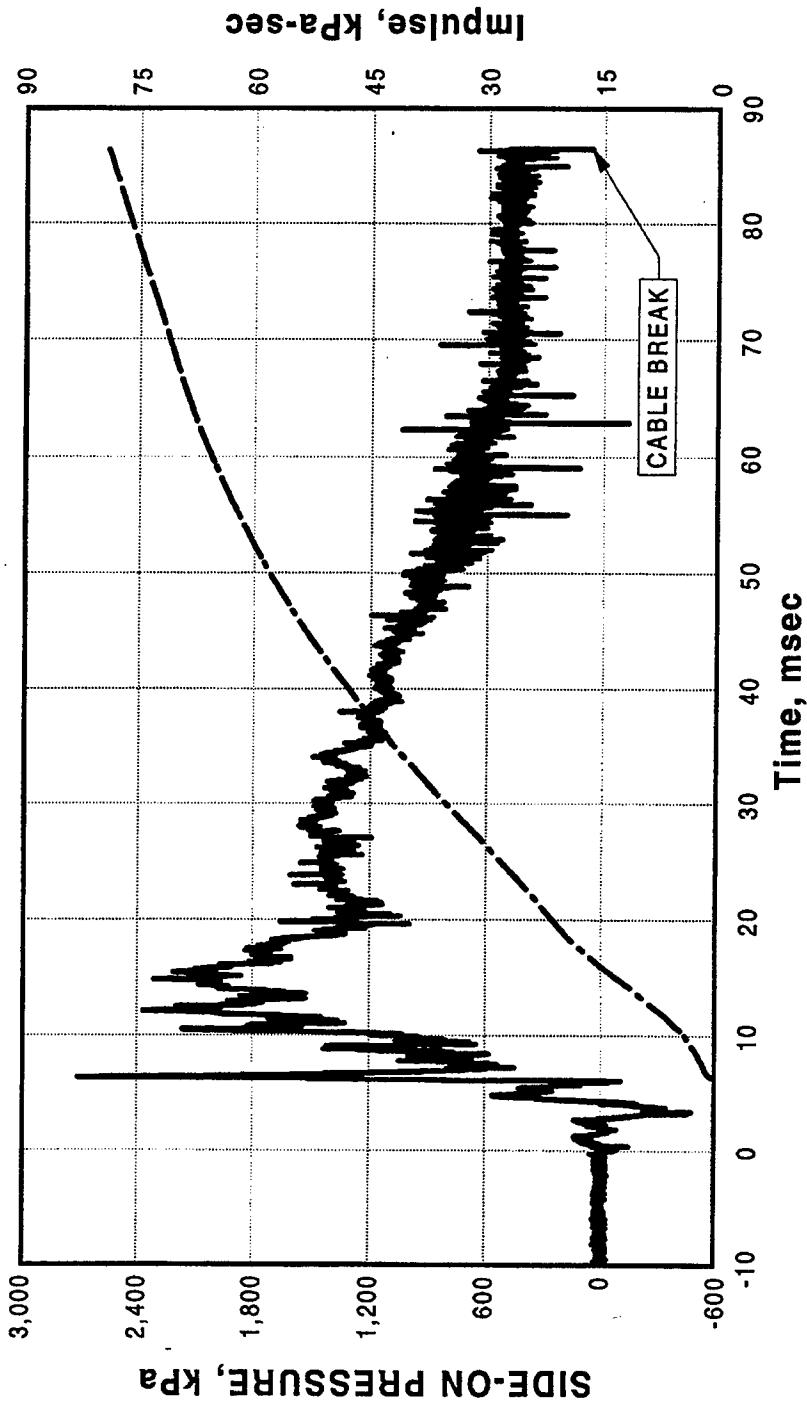


Figure B4. Gage 19ABSO airblast overpressure- and impulse-time-histories (90 msec record), Singapore Ground Shock Test.

# 18ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=917.1166, CBS=0.323935

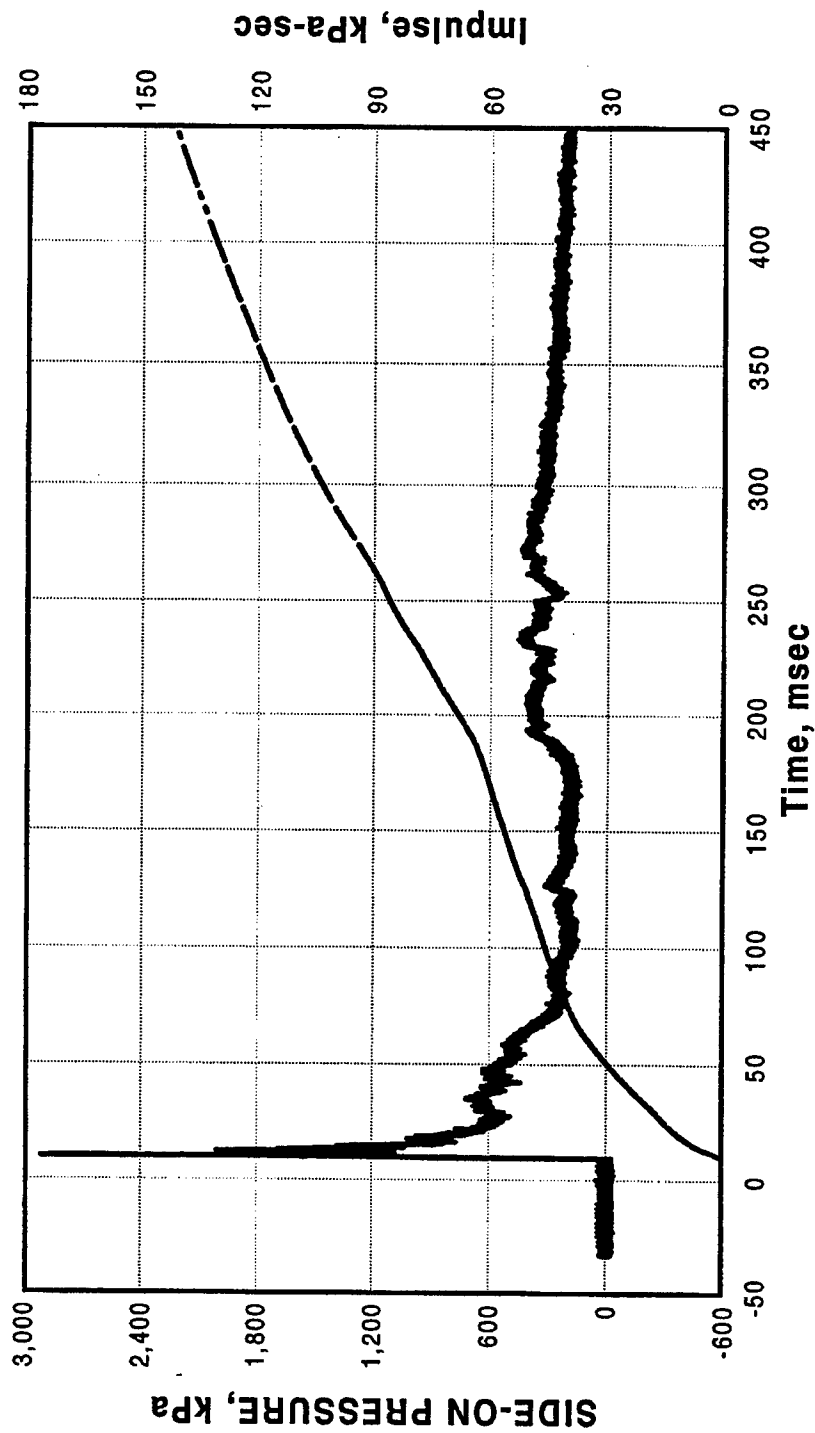


Figure B5. Gage 18ABSO airblast overpressure- and impulse-time-histories (450 msec record), Singapore Ground Shock Test.

# 18ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=917.1166, CBS=0.323935

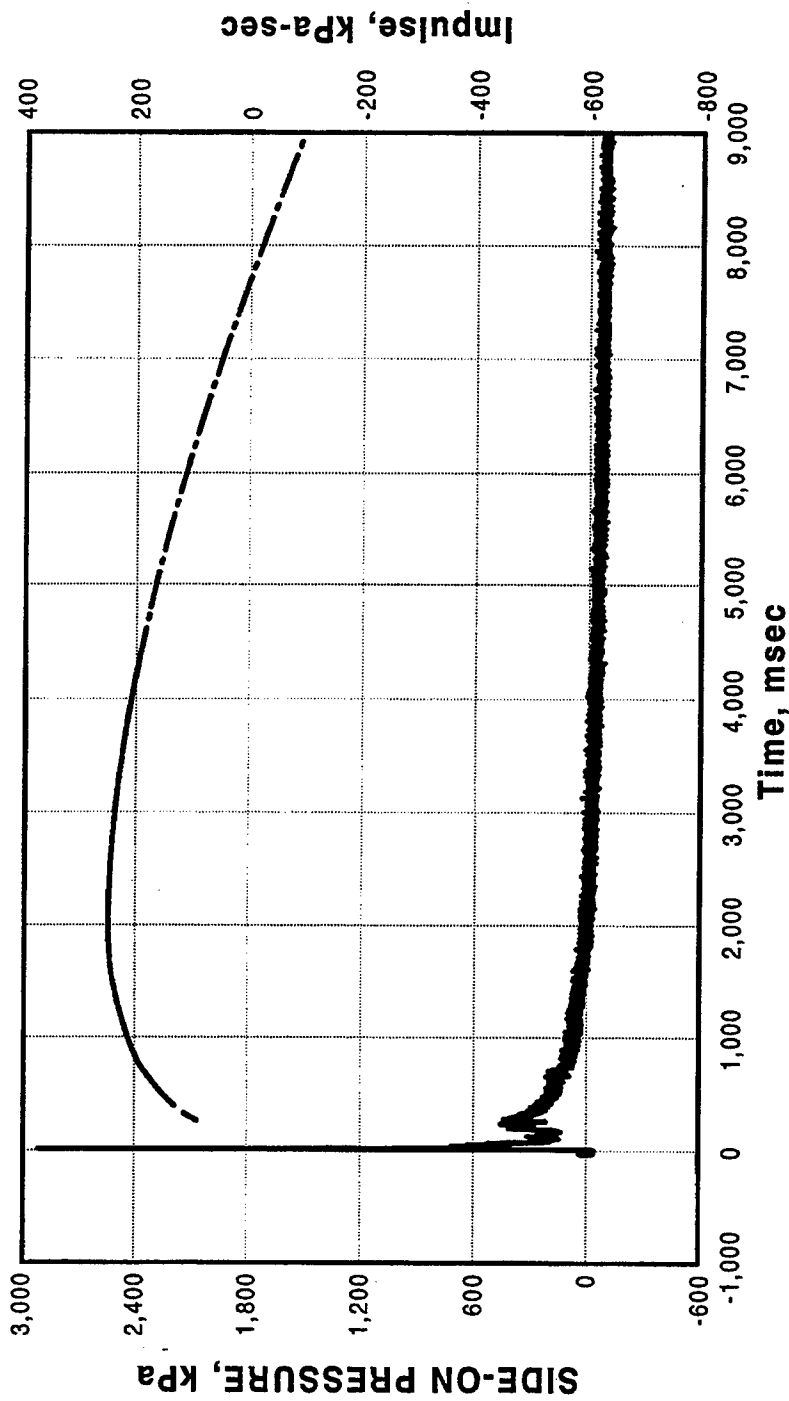


Figure B6. Gage 18ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.



# 16ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=388.5679, CBS=0.000730052

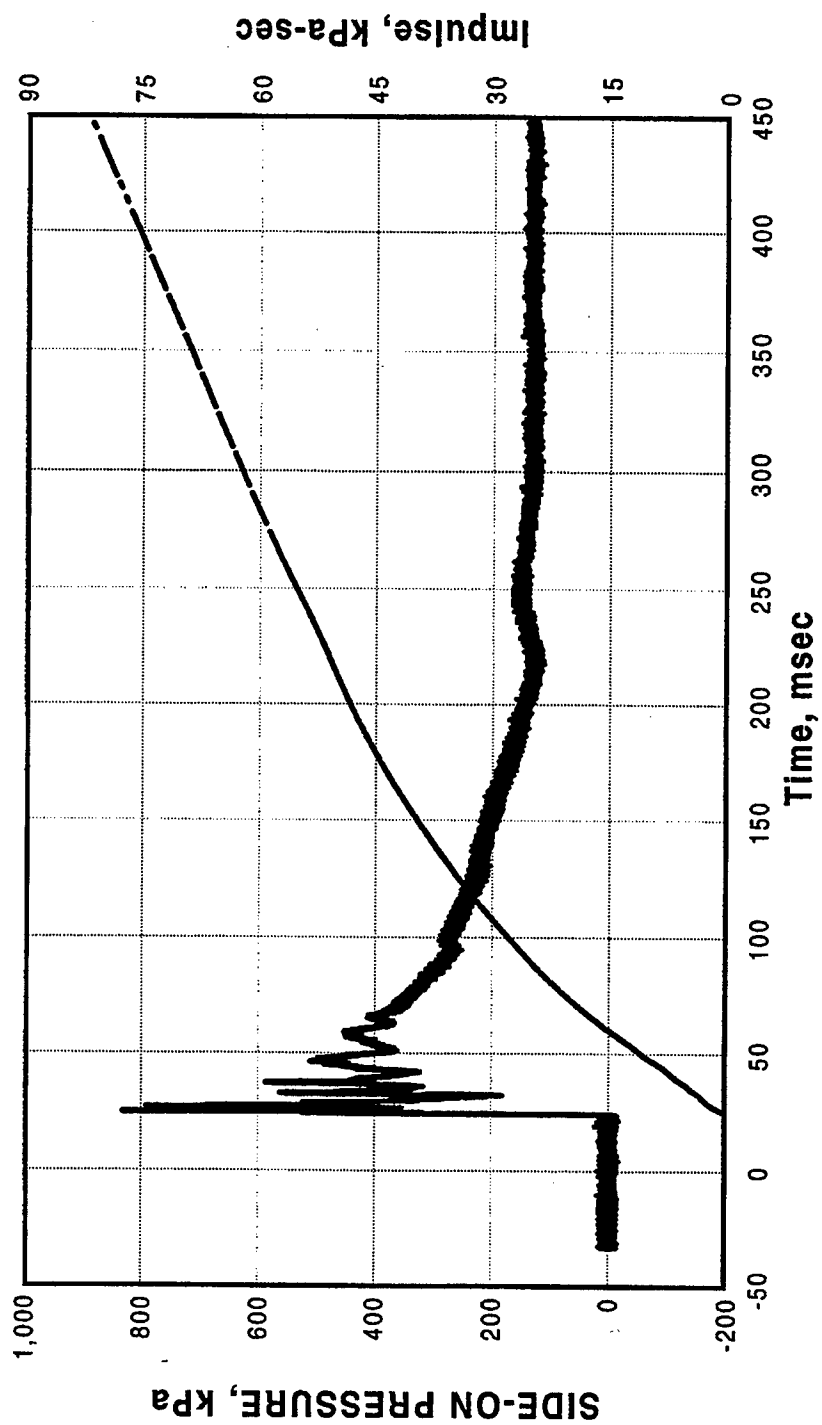


Figure B7. Gage 16ABSO airblast overpressure- and impulse-time-histories (450 msec record), Singapore Ground Shock Test.

# 16ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=388.5679, CBS=0.000730052

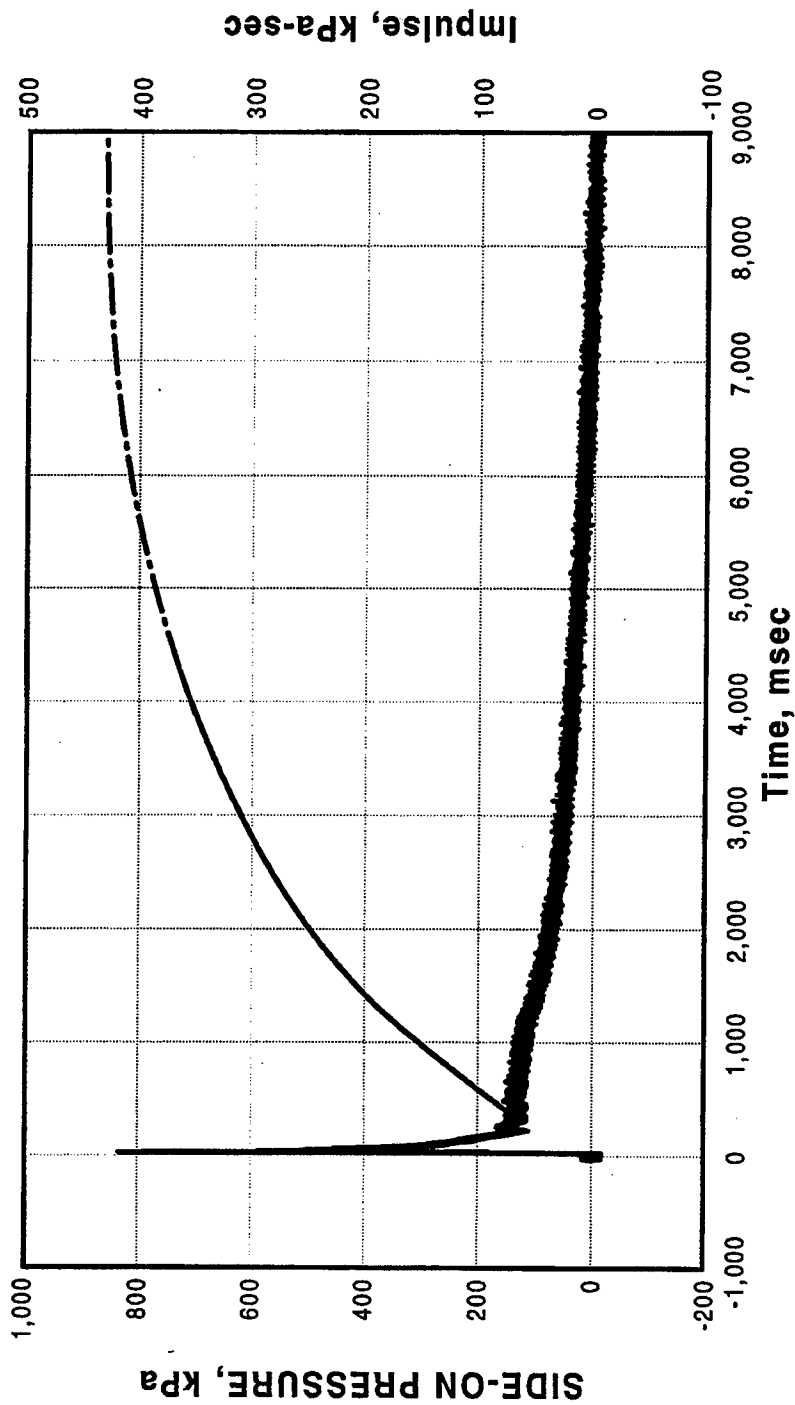


Figure B8. Gage 16ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.

# 11ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=250.7745, CBS=0.290136

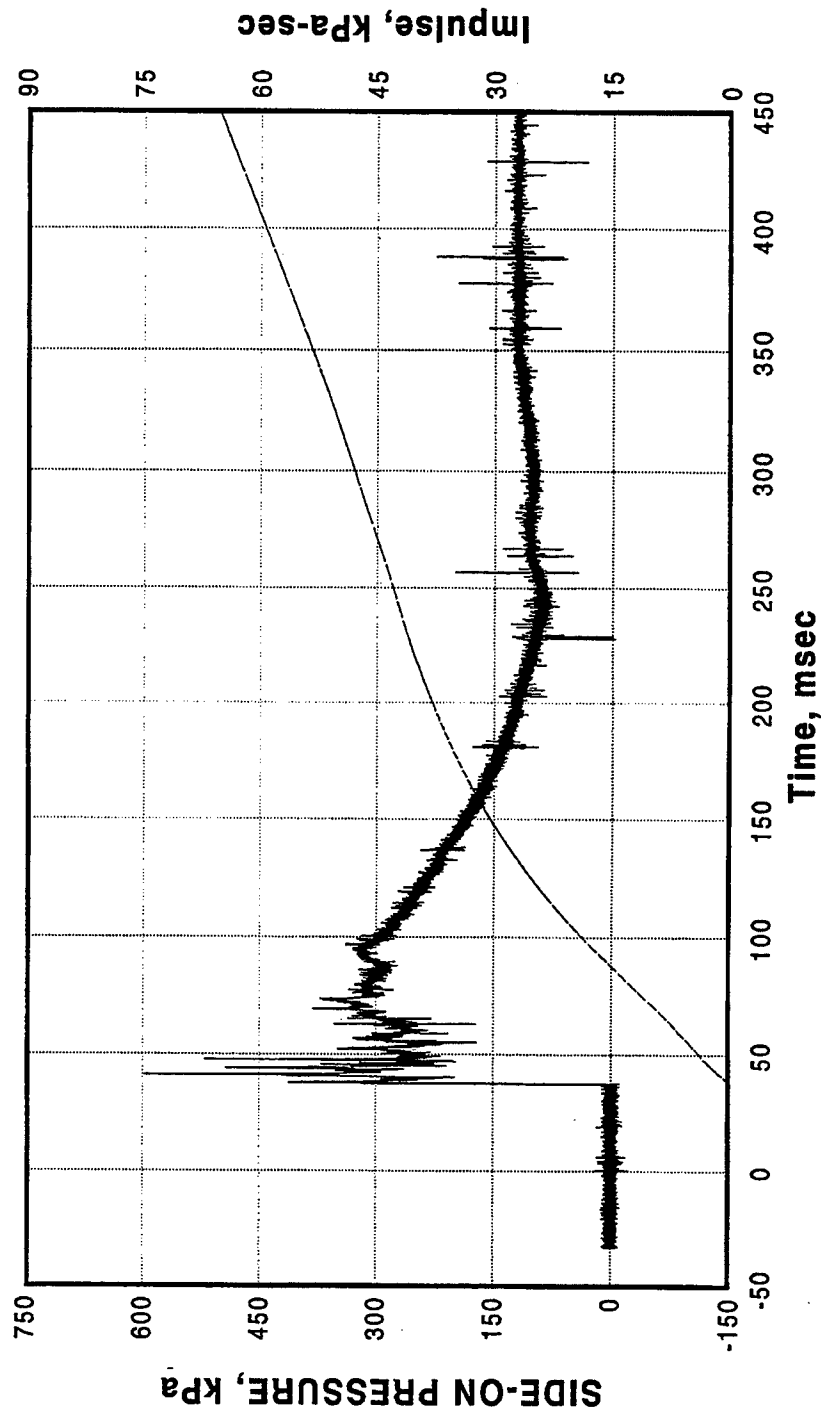


Figure B9. Gage 11ABSO airblast overpressure- and impulse-time-histories (450 msec record), Singapore Ground Shock Test.

# 11ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=250.7745, CBS=0.290136

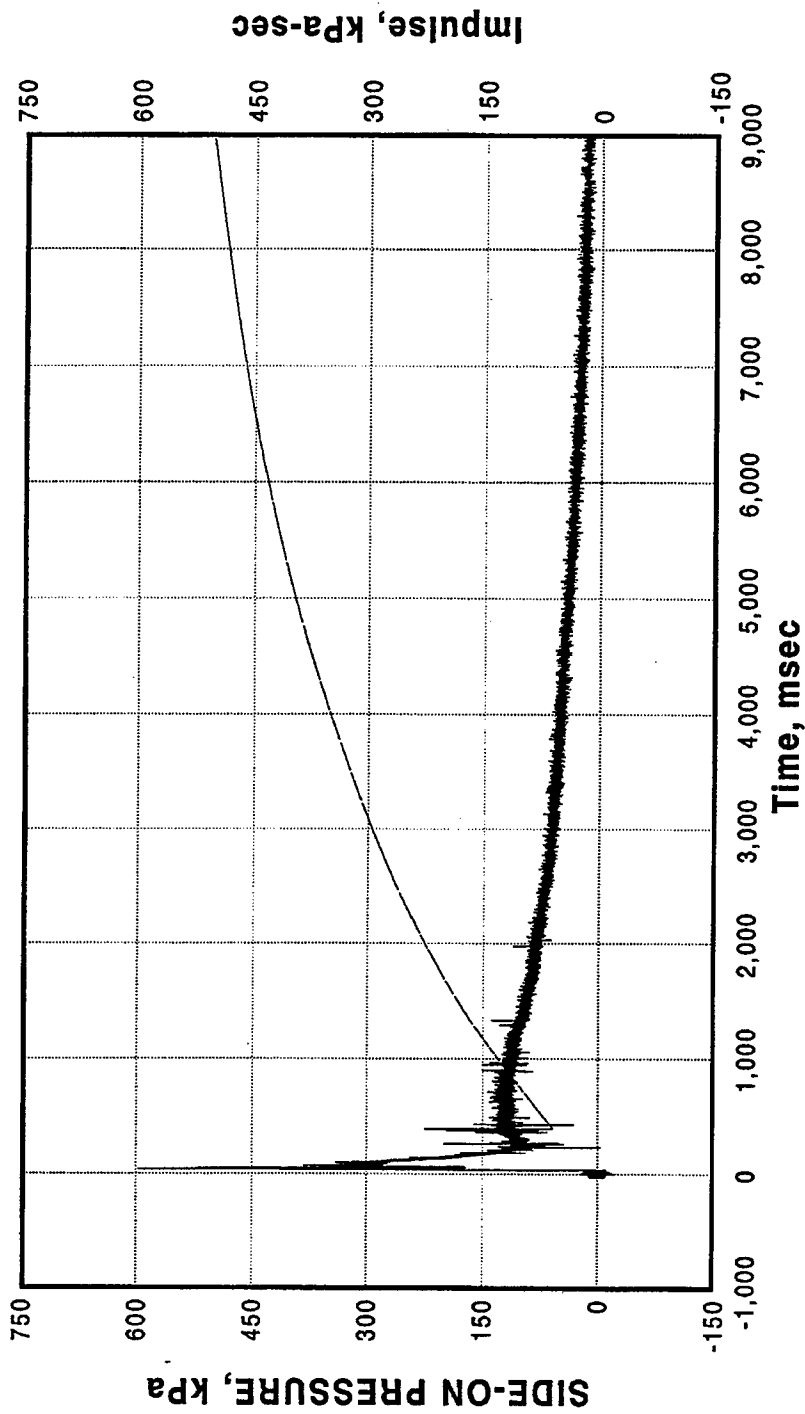


Figure B10. Gage 11ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.

# 10A-ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=97.76835, CBS=0.0657466

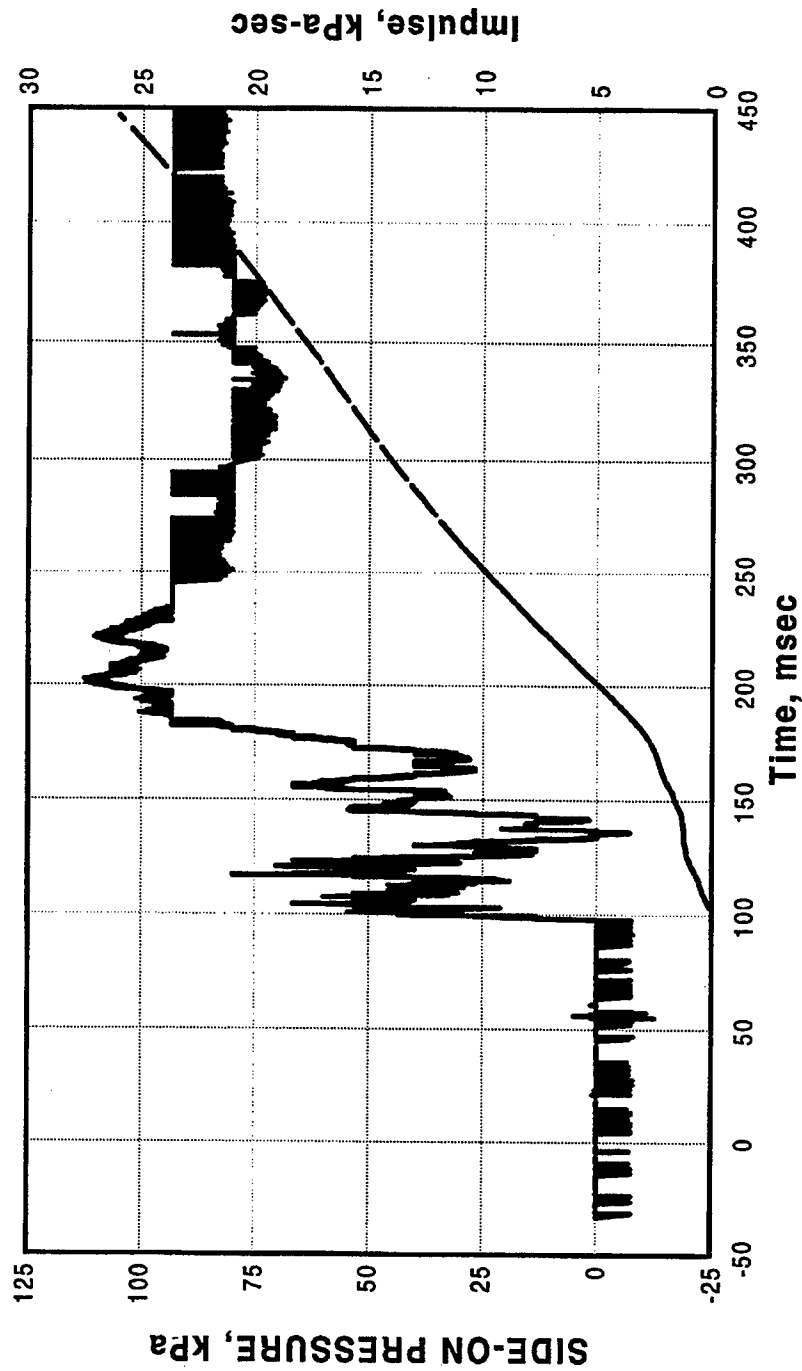


Figure B11. Gage 10A-ABSO airblast overpressure- and impulse-time-histories (450 msec record), Singapore Ground Shock Test.

# 10A-ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=97.76835, CBS=0.0657466

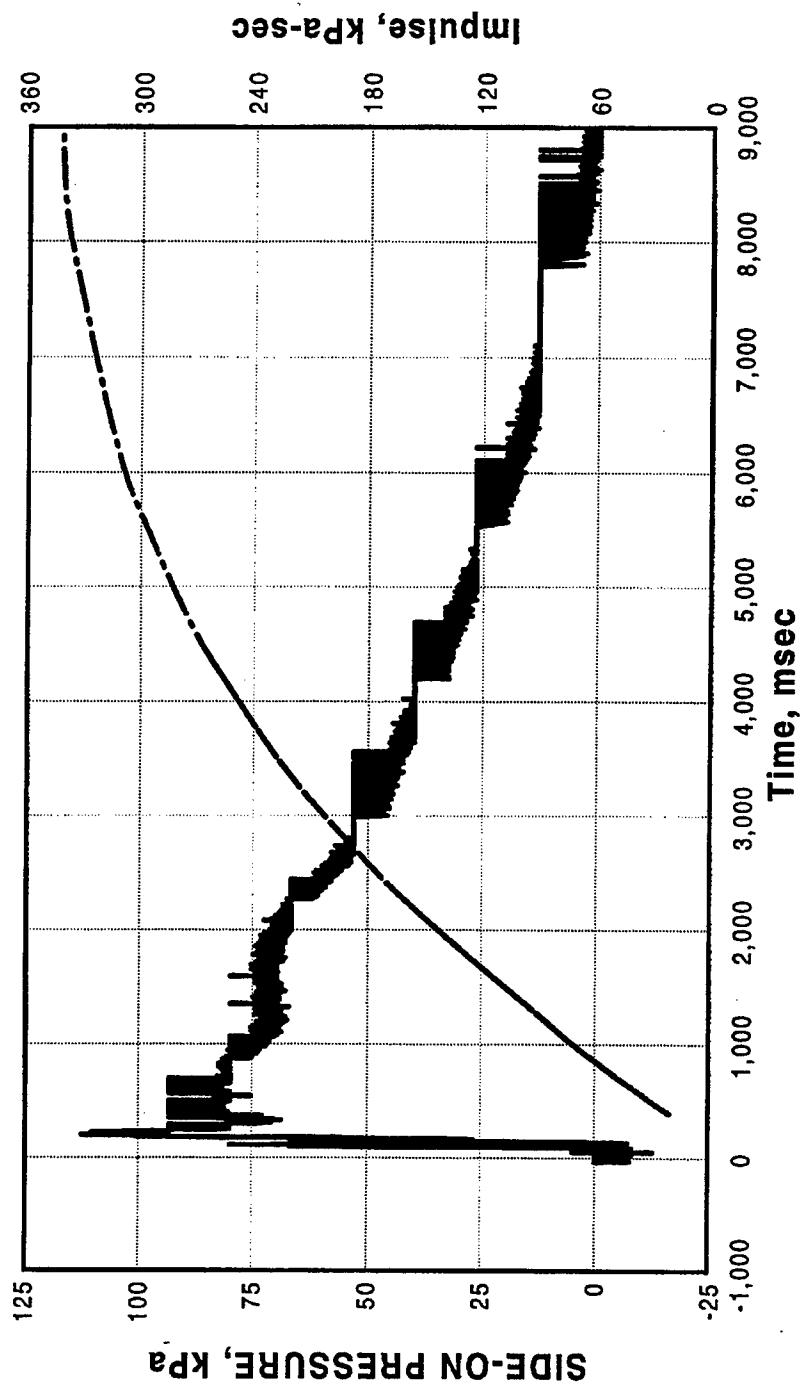


Figure B12. Gage 10A-ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.

# 10B-ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=125.2923, CBS=0.00524016

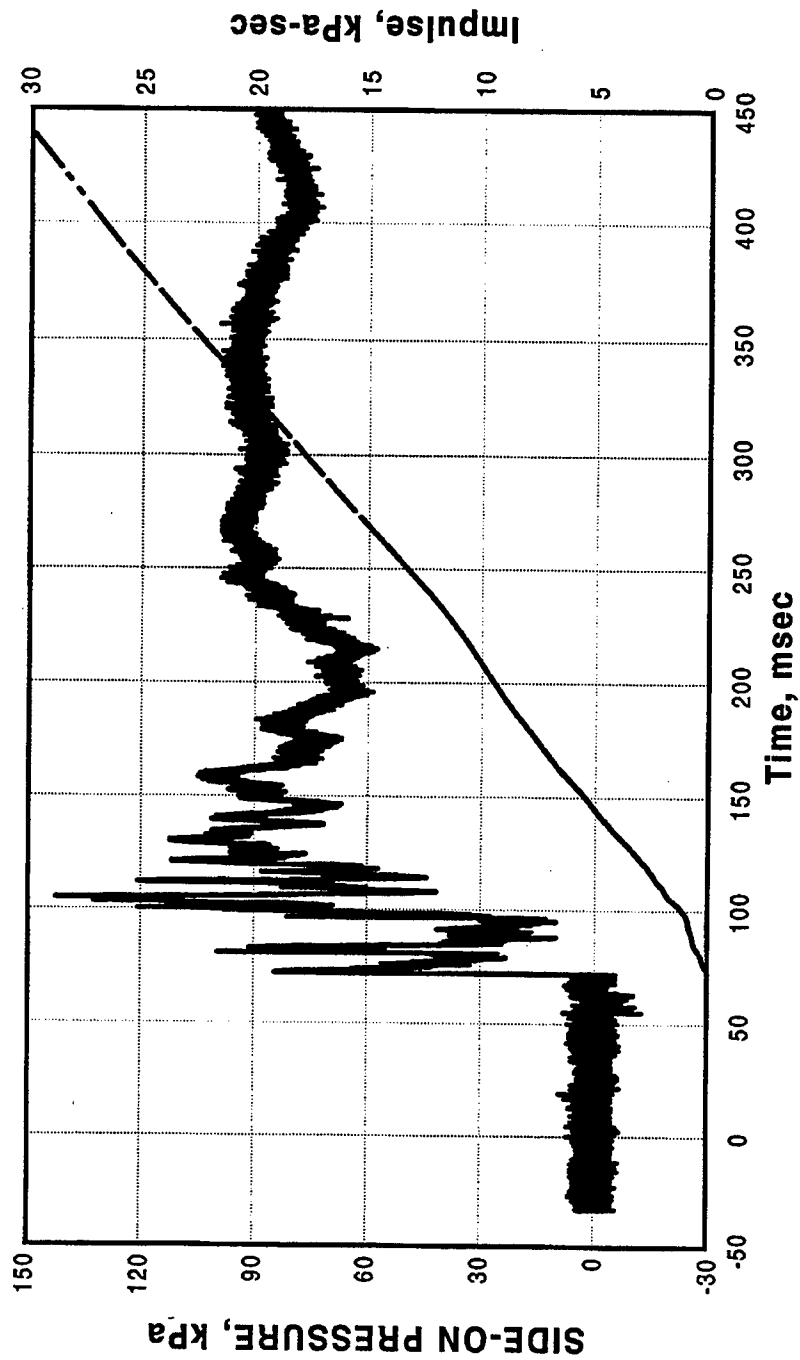


Figure B13. Gage 10B-ABSO airblast overpressure- and impulse-time-histories (450 msec record), Singapore Ground Shock Test.

# 10B-ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=125.2923, CBS=0.00524016

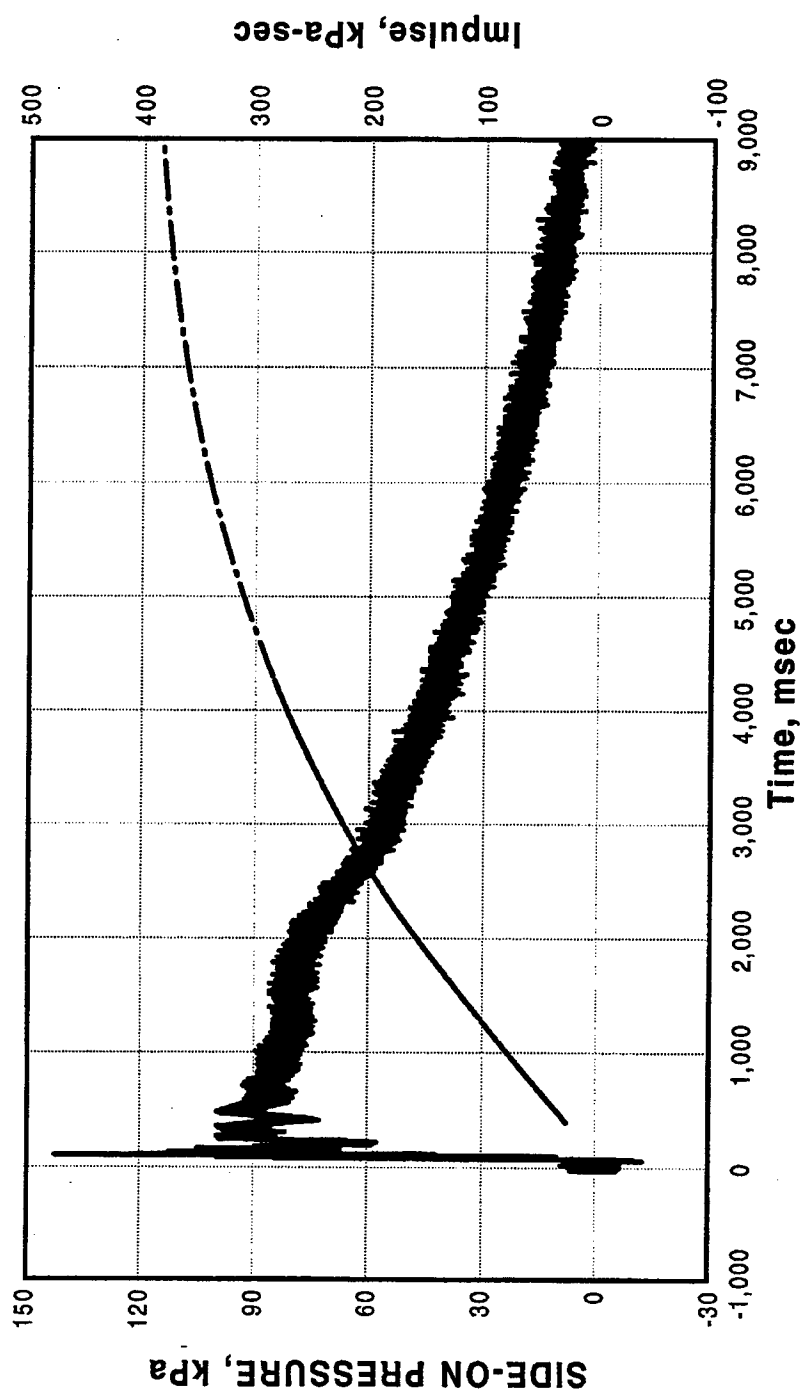


Figure B14. Gage 10B-ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.



# 10D-ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=97.71223, CBS=0.00724495

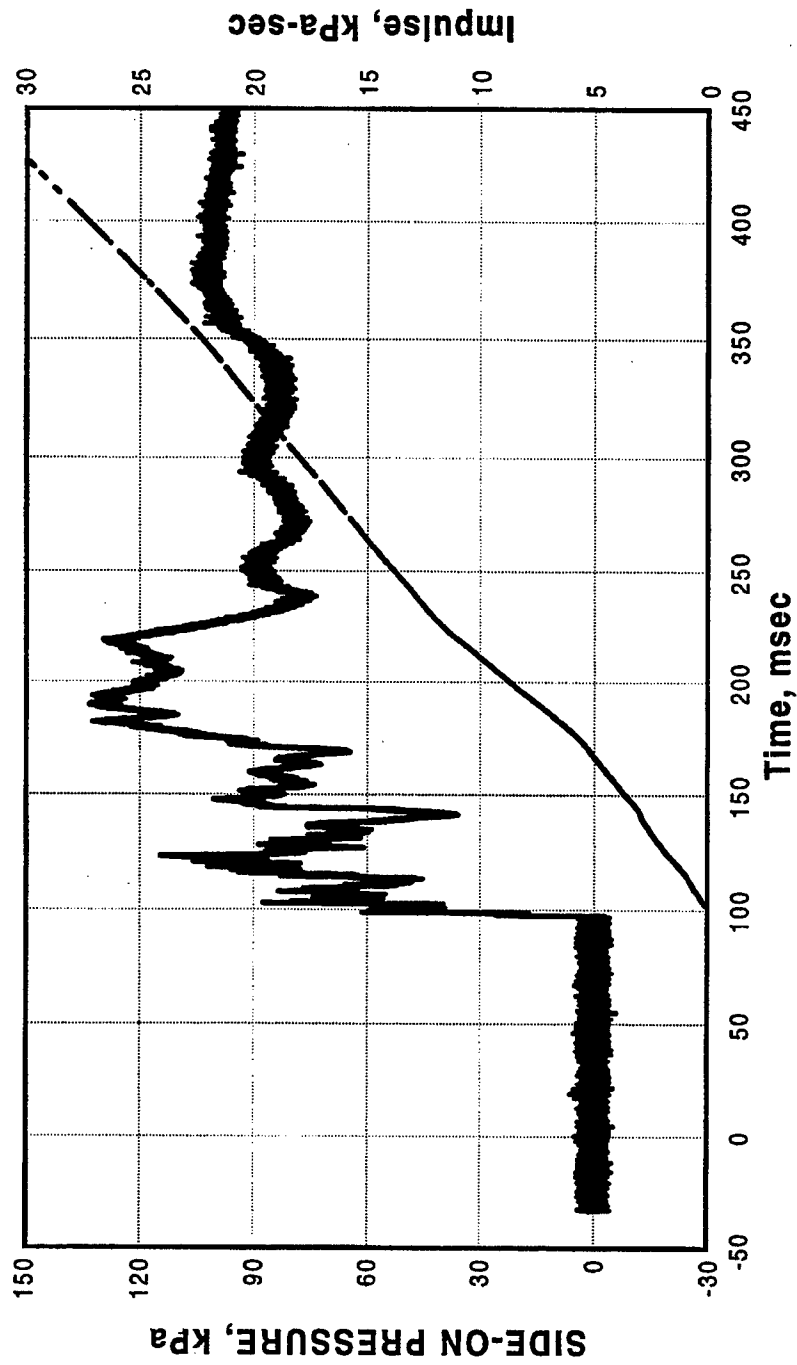


Figure B15. Gage 10D-ABSO airblast overpressure- and impulse-time-histories (450 msec record), Singapore Ground Shock Test.

# 10D-ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35  
Cal val=97.71223, CBS=0.00724495

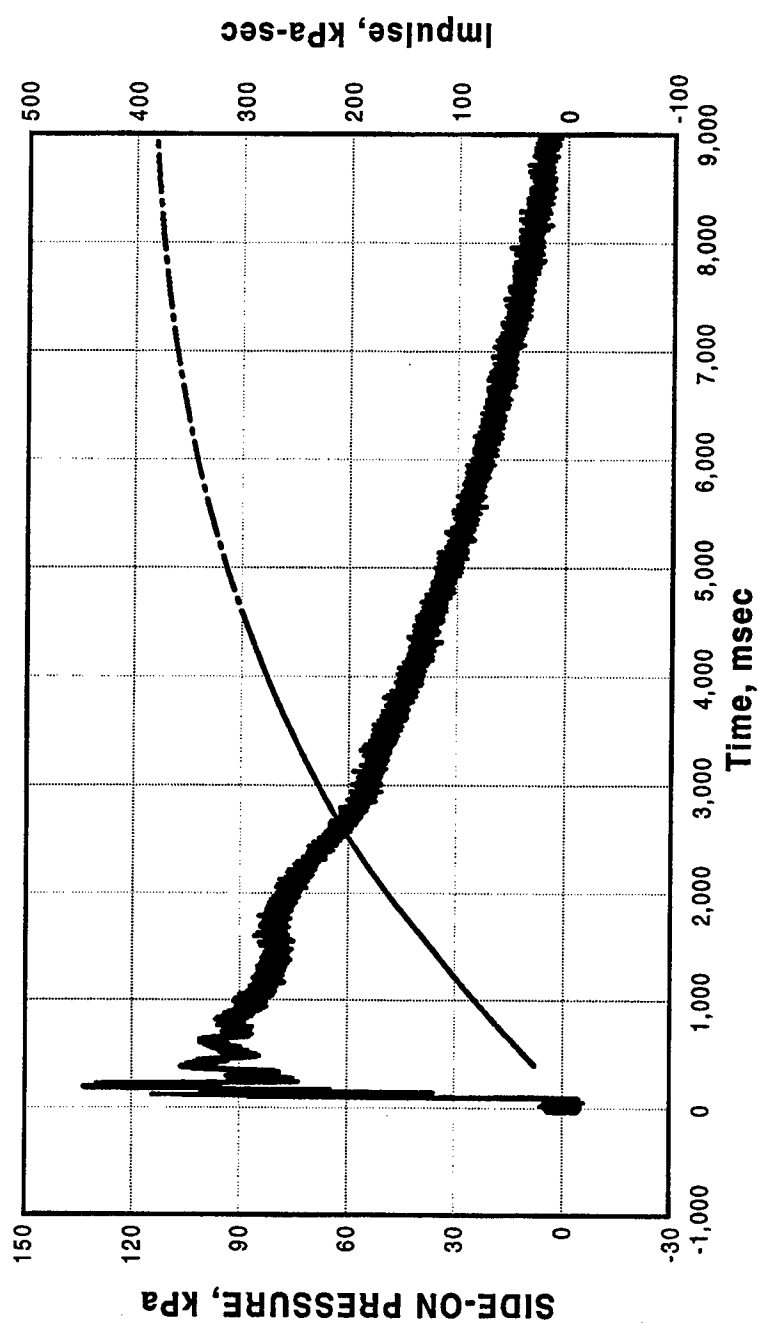


Figure B16. Gage 10D-ABSO airblast overpressure- and impulse-time-histories  
(9 sec record), Singapore Ground Shock Test.

# 4ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=28.09811, CBS=0.0338342 from -32.764 to 12844.03

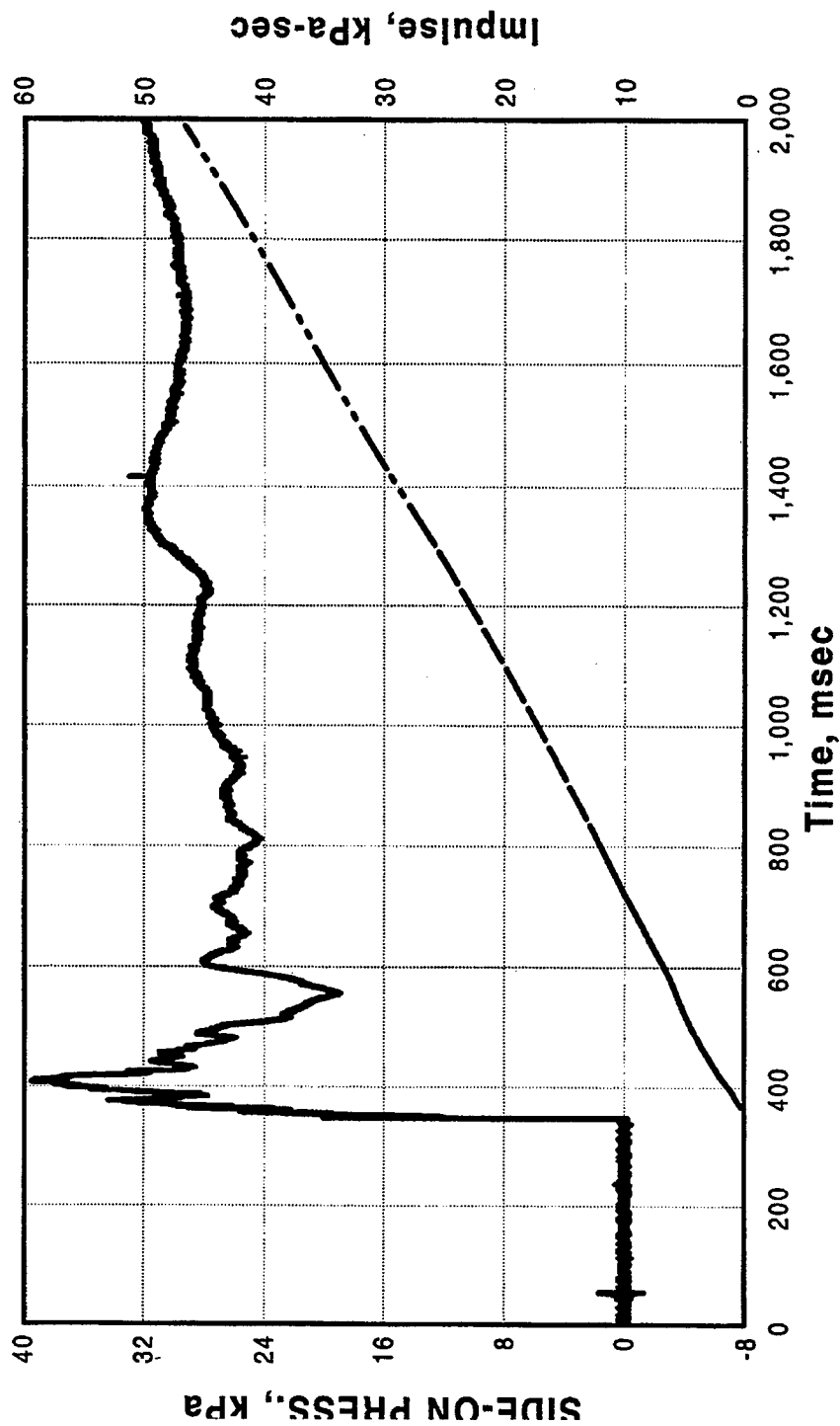


Figure B17. Gage 4ABSO airblast overpressure- and impulse-time-histories (2 sec record), Singapore Ground Shock Test.

# 4ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=28.09811, CBS=0.0338342 from -32.764 to 12844.03

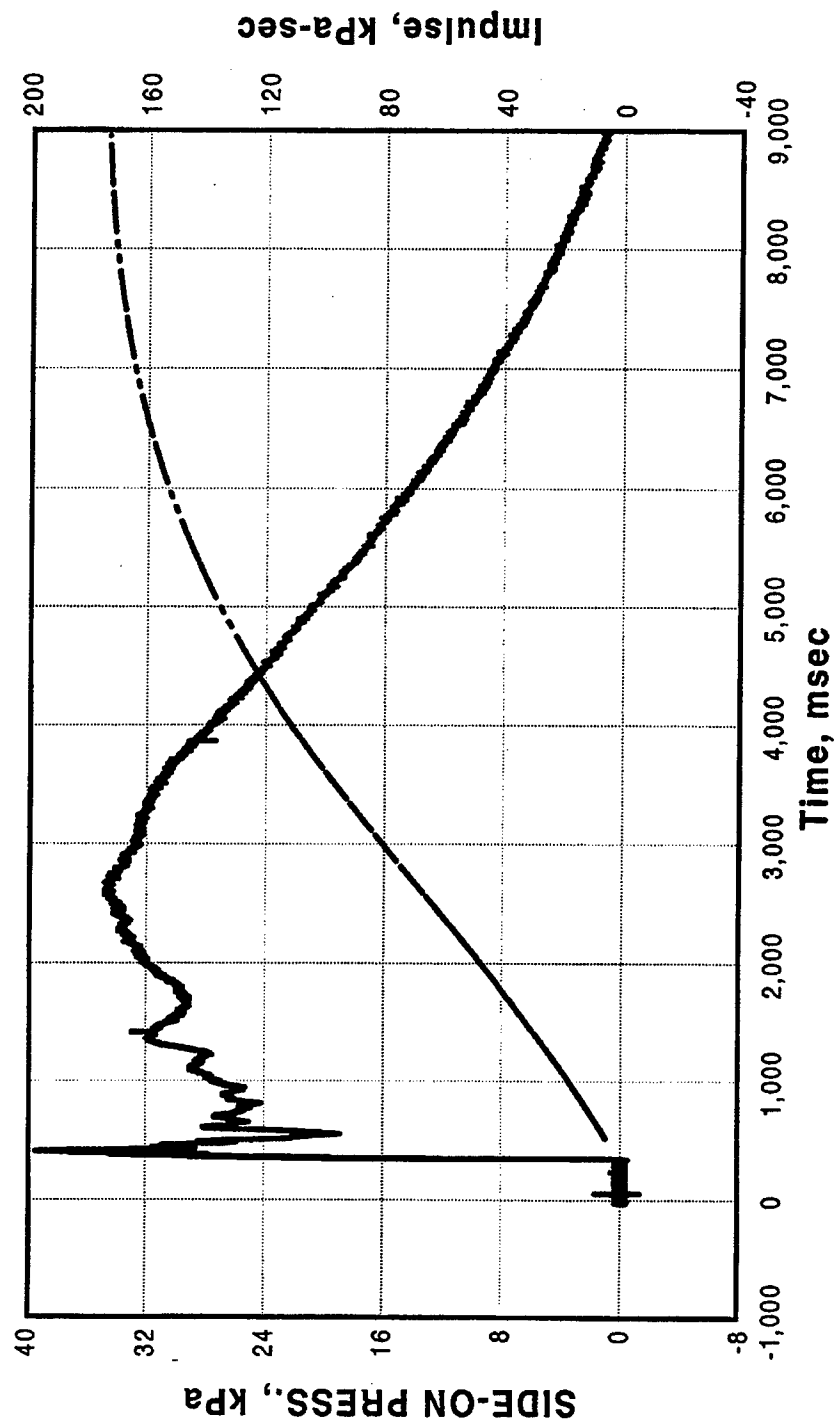


Figure B18. Gage 4ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.

# 3ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=15.81394, CBS=0.00659208

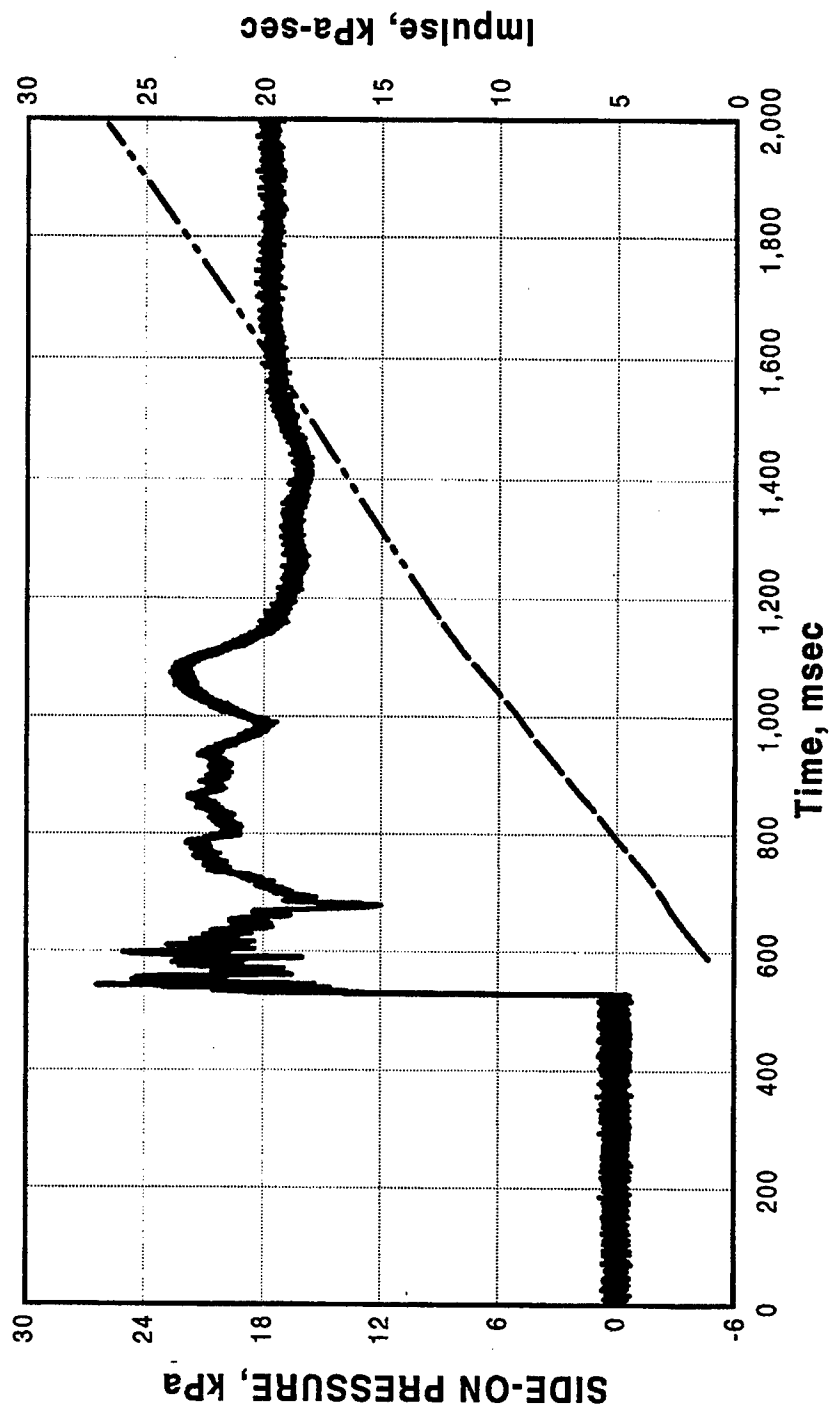


Figure B19. Gage 3ABSO airblast overpressure- and impulse-time-histories (2 sec record), Singapore Ground Shock Test.

# 3ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=15.81394, CBS=0.00659208

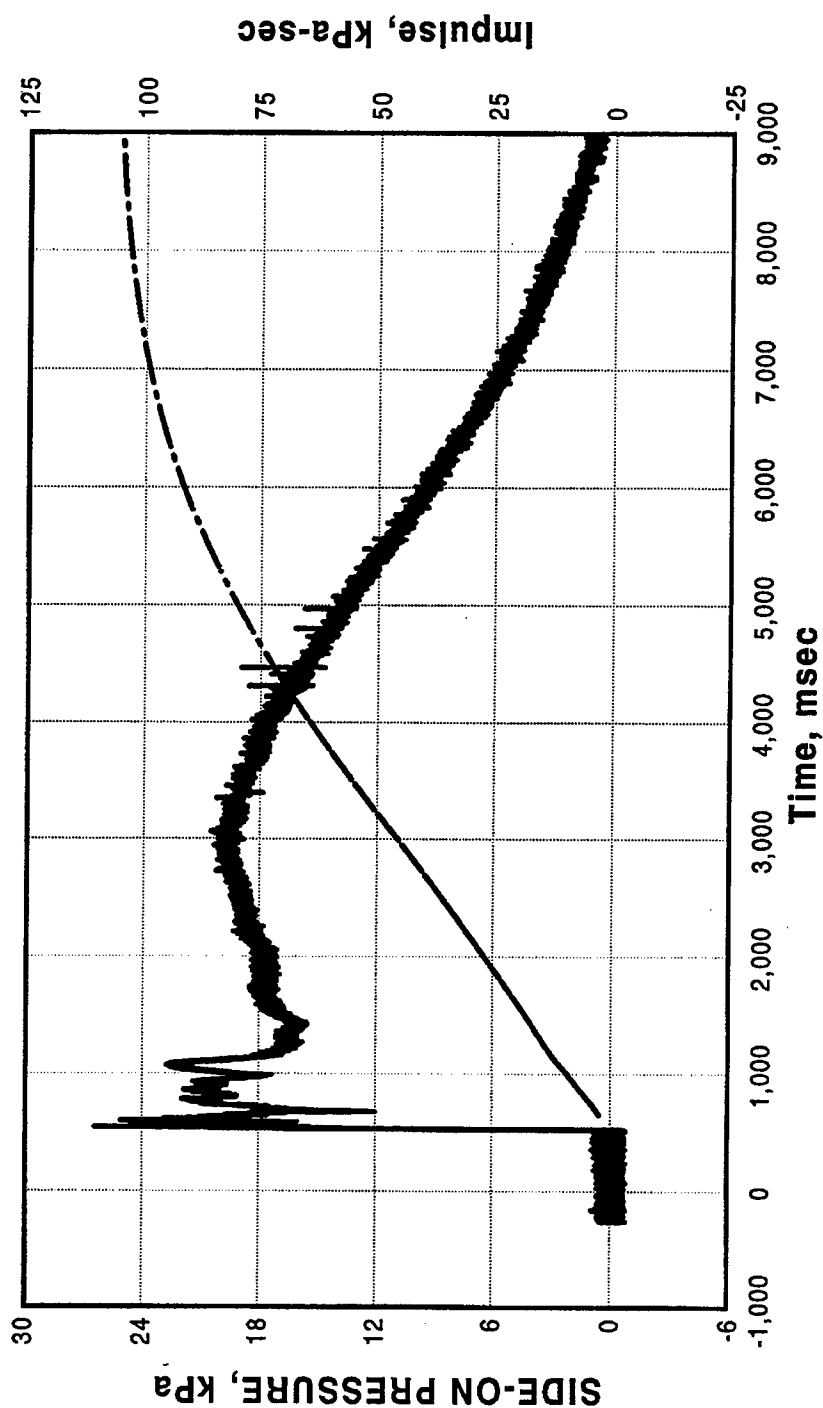


Figure B20. Gage 3ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.

# 1ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=10.50718, CBS=-0.00128758

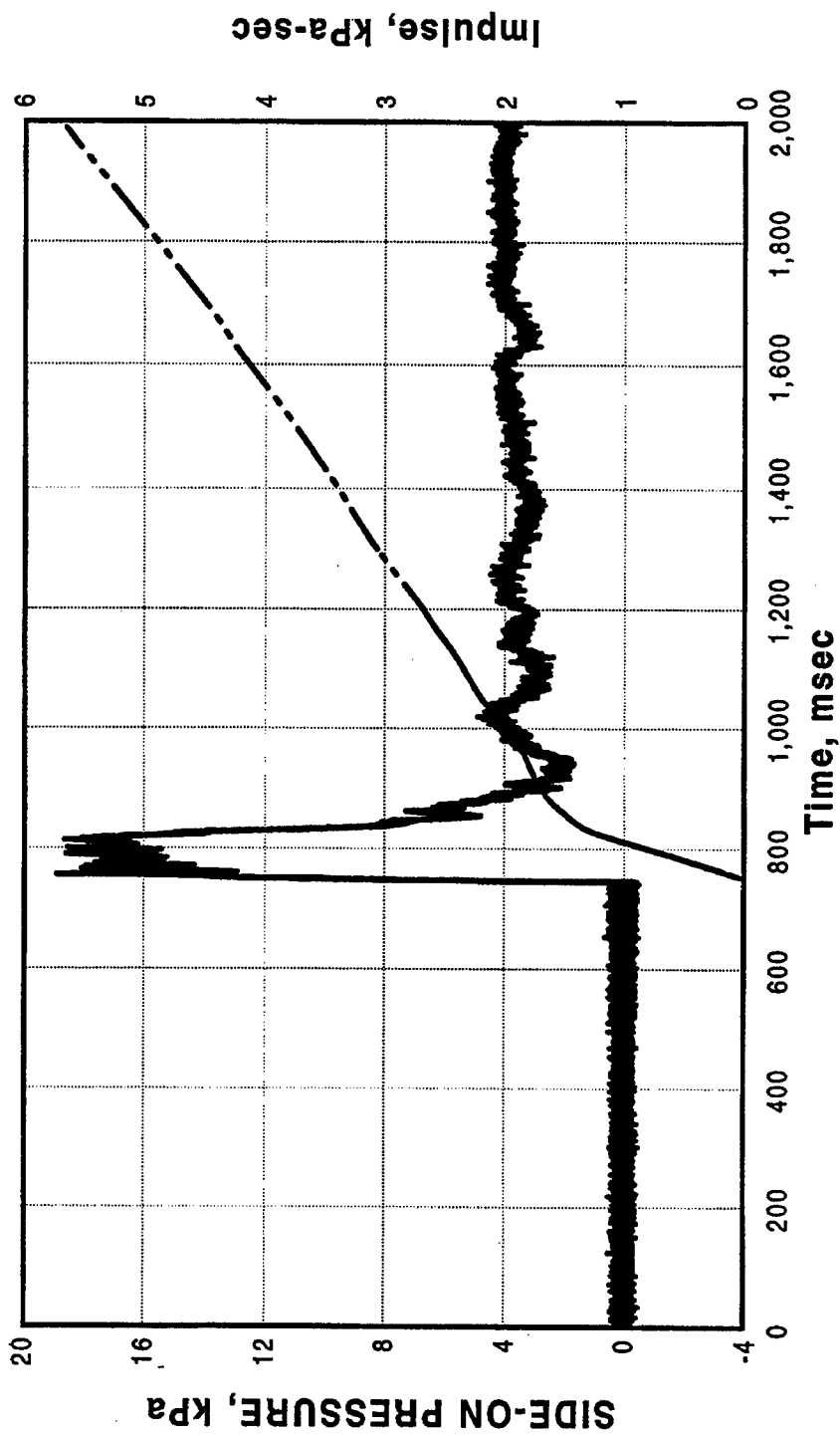


Figure B21. Gage 1ABSO airblast overpressure- and impulse-time-histories (2 sec record), Singapore Ground Shock Test.

# 1ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=10.50718, CBS=-0.00128758

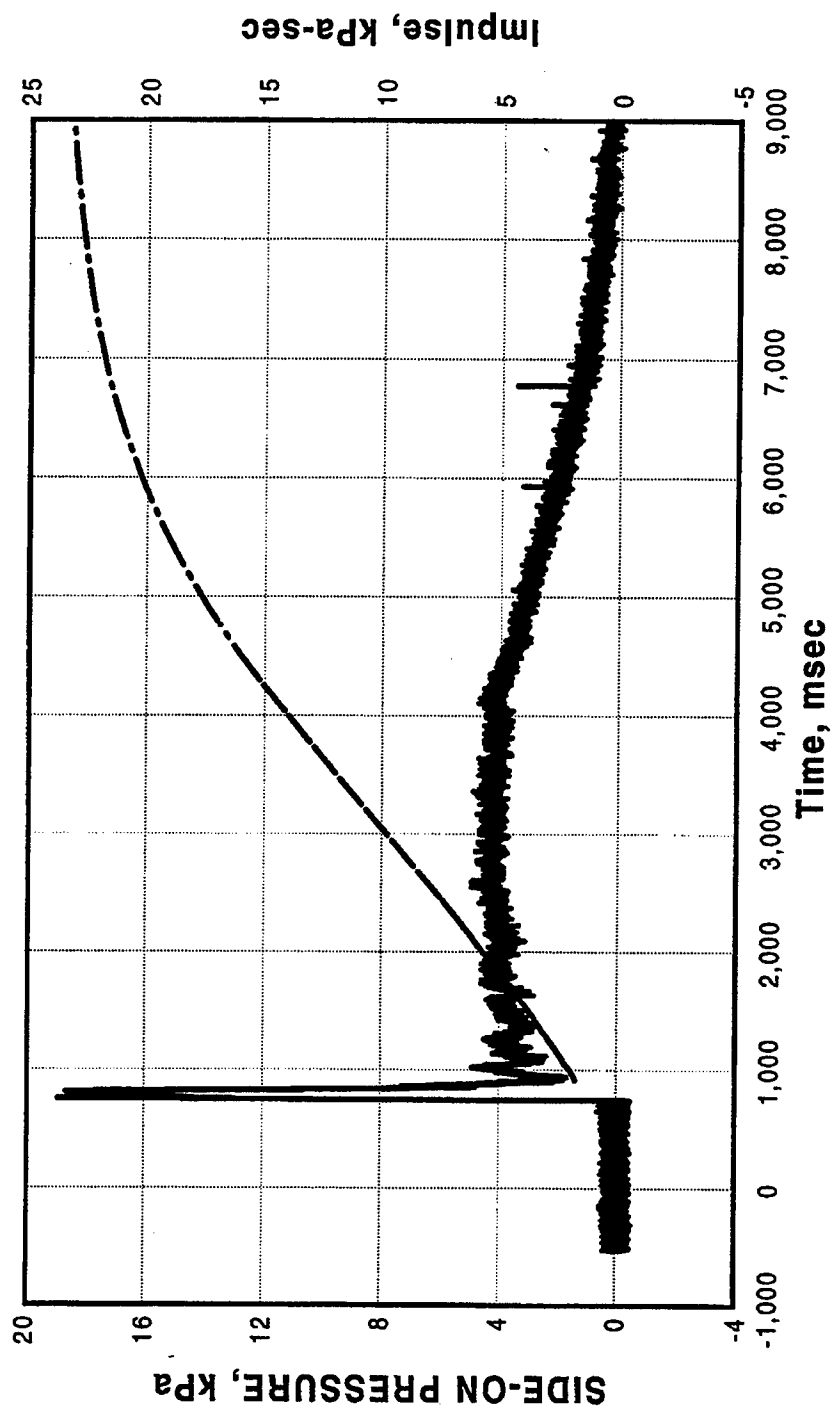


Figure B22. Gage 1ABSO airblast overpressure- and impulse-time-histories (9 sec record), Singapore Ground Shock Test.



# 59ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=0.5007814, CBS=-0.00587689

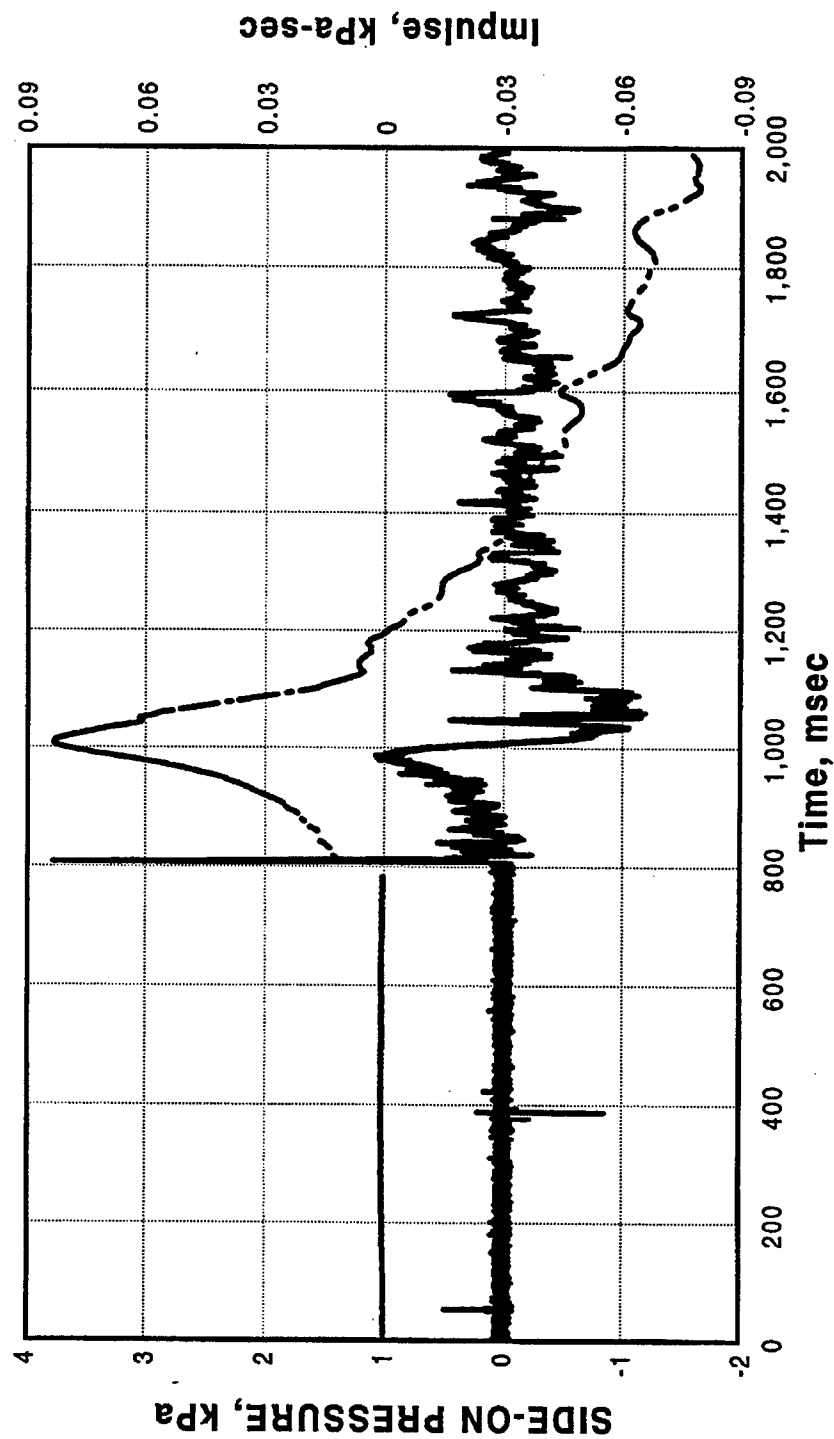


Figure B23. Gage 59ABSO free-field overpressure- and impulse-time-histories  
(2 sec record), Singapore Ground Shock Test.

# 60ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=0.2948767, CBS=-0.222867

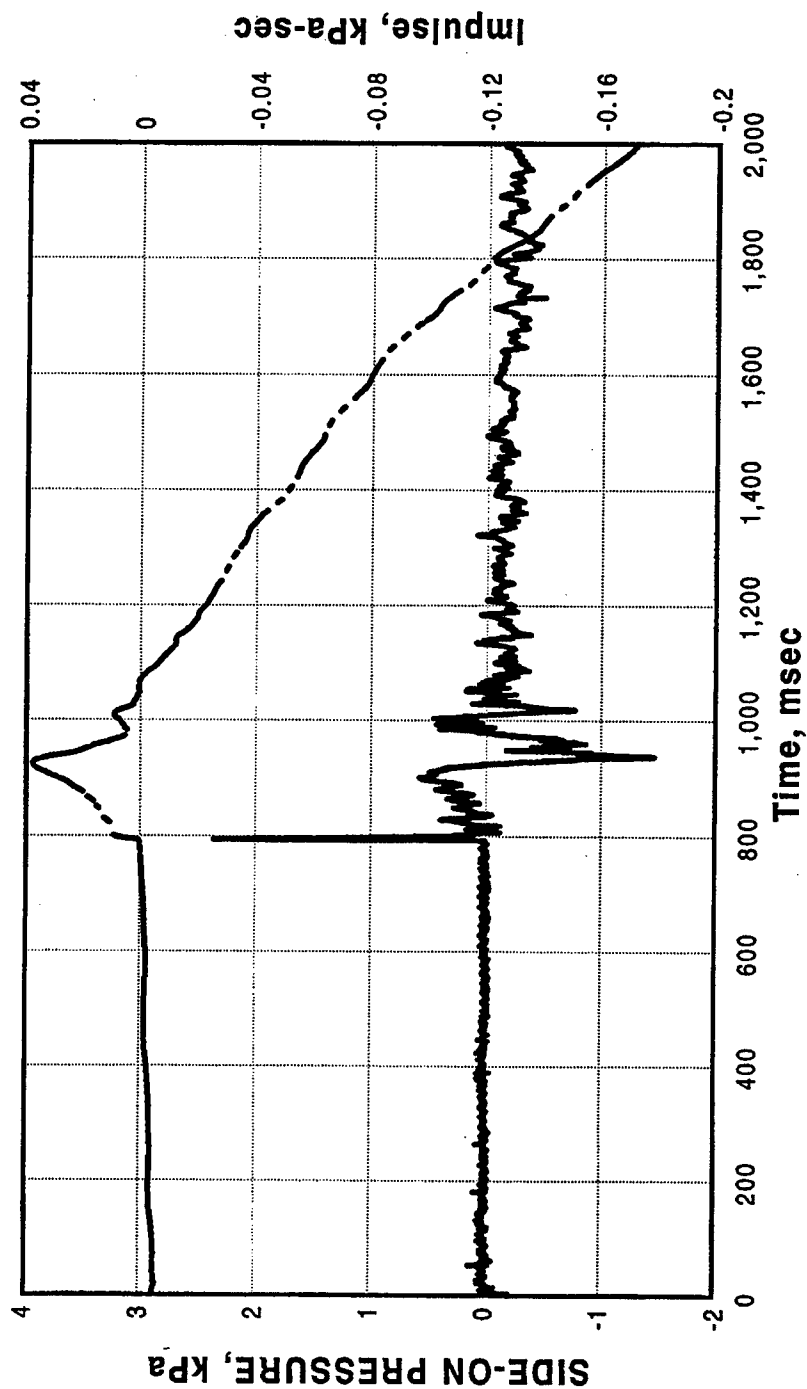


Figure B24. Gage 60ABSO free-field overpressure- and impulse-time-histories (2 sec record), Singapore Ground Shock Test.

# 63ABSO REPUBLIC OF SINGAPORE GROUND SHOCK TEST

06-18-1996 02:00:35

Cal val=0.1144909, CBS=-0.00388012

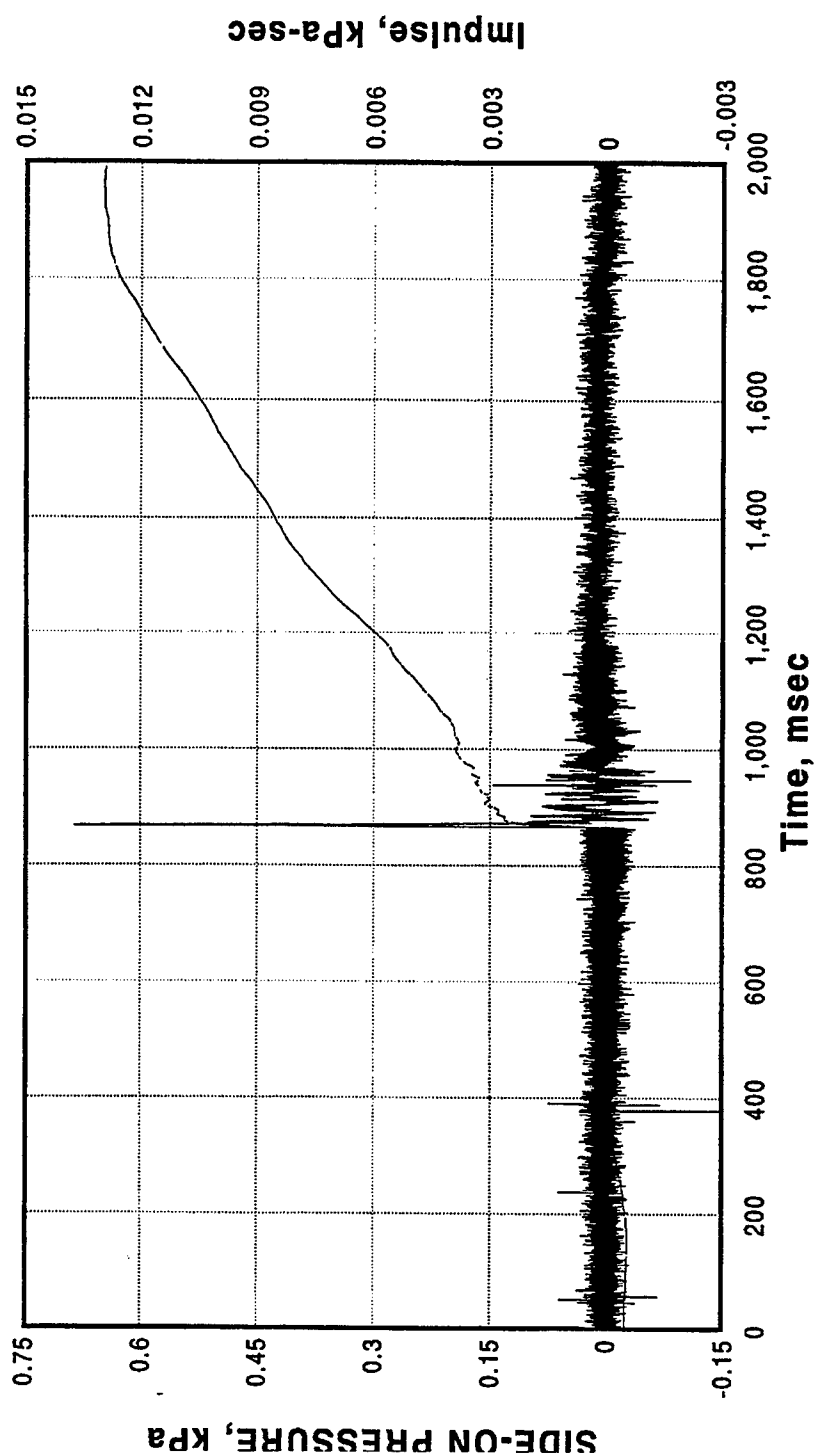


Figure B25. Gage 63ABSO free-field overpressure- and impulse-time-histories (2 sec record), Singapore Ground Shock Test.

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> April 2000			<b>2. REPORT TYPE</b> Final report		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b> 1996 Singapore Ground Shock Test					<b>5a. CONTRACT NUMBER</b>	
					<b>5b. GRANT NUMBER</b>	
					<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> Donald W. Murrell, Charles E. Joachim					<b>5d. PROJECT NUMBER</b>	
					<b>5e. TASK NUMBER</b>	
					<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> U.S. Army Engineer Research and Development Center Waterways Experiment Station 3909 Halls Ferry Road Vicksburg, MS 39180-6199					<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  ERDC/SL TR-00-1	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Lands and Estates Organization Ministry of Defence 1 Depot Road, #12-05 Singapore 109679 Republic of Singapore					<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
					<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b>  Approved for public release, distribution unlimited.						
<b>13. SUPPLEMENTARY NOTES</b>						
<b>14. ABSTRACT</b> The 1996 Singapore Ground Shock Test was conducted to document the ground shock and surface ground motions produced by a simulated accidental detonation of munitions in a 1/3-scale underground storage chamber at a nominal loading density of 10 kg/cubic-m. A secondary objective was to record the airblast levels produced in the connecting tunnels and beyond the tunnel portal. The explosive charge consisted of 696.6 kg of Composition B explosive. The test chamber was located at a depth of approximately 115 m in a limestone geology. The ground motion data from the gages installed in the vertical boorehole are in good agreement with data from previous experiments (UAST) at this site. Comparison of these data and surface values shows that both sets attenuate at the rate of distance to the-2.5 power. The surface motion reflection factor is slightly greater than the theoretical free-surface value but is in good agreement with reflection factors of 3 to 5 that have been observed on underground nuclear tests.						
<b>15. SUBJECT TERMS</b> Ammunition storage, Ground shock, Seismic ground motions, Surface ground motions, Underground magazines						
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>	
<b>a. REPORT</b> UNCLASSIFIED	<b>b. ABSTRACT</b> UNCLASSIFIED	<b>c. THIS PAGE</b> UNCLASSIFIED			<b>19b. TELEPHONE NUMBER (include area code)</b>	